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Improved NP-Inapproximability for 2-Variable Linear Equations

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Abstract: An instance of the 2-Lin(2) problem is a system of equations of the form "$x_i + x_j = b \pmod 2$." Given such a system in which it is possible to satisfy all but an ε fraction of the equations, we show it is NP-hard to satisfy all but a $C\varepsilon$ fraction of equations, for any $C < 11/8 = 1.375$ (and any $0 < \varepsilon \le 1/8$). The previous best result, standing for over 15 years, had $5/4$ in place of $11/8$. Our result provides the best known NP-hardness even for the Unique-Games problem, and it also holds for the special case of Max-Cut. The

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precise factor $11/8$ is unlikely to be best possible; we also give a conjecture concerning analysis of Boolean functions which, if true, would yield a larger hardness factor of $3/2$.

Our proof is by a modified gadget reduction from a pairwise-independent predicate. We also show an inherent limitation to this type of gadget reduction. In particular, any such reduction can never establish a hardness factor C greater than 2.54. Previously, no such limitations on gadget reductions was known.

1 Introduction

The well-known constraint satisfaction problem (CSP) 2-Lin(q) is defined as follows: Given n variables $x_1, \ldots, x_n$, as well as a system of equations (constraints) of the form "$x_i - x_j = b \pmod q$" for constants $b \in \mathbb{Z}_q$, the task is to assign values from $\mathbb{Z}_q$ to the variables so that there are as few unsatisfied constraints as possible. It is known [18, 20] that, from an approximability standpoint, this problem is equivalent to the notorious Unique-Games problem [17]. The special case of $q = 2$ is particularly interesting and can be equivalently stated as follows: Given a "supply graph" G and a "demand graph" H over the same set V of vertices, partition V into two parts so as to minimize the total number of cut supply edges and uncut demand edges. The further special case when the supply graph G is empty (i. e., every equation is of the form $x_i - x_j = 1 \pmod 2$) is equivalent to the Max-Cut problem.

Let us say that an algorithm guarantees an $(\varepsilon, \varepsilon')$-*approximation* if, given any instance in which the best solution violates at most an ε-fraction of the constraints, the algorithm finds a solution violating at most an ε'-fraction of the constraints. If an algorithm guarantees $(\varepsilon, C\varepsilon)$-approximation for every ε then we also say that it is a *factor-C approximation*. To illustrate the notation we recall two simple facts. On the one hand, for each fixed q, there is a trivial greedy algorithm which $(0,0)$-approximates 2-Lin(q). On the other hand, $(\varepsilon, \varepsilon)$-approximation is NP-hard for every $0 < \varepsilon < 1/q$; in particular, factor-1 approximation is NP-hard.

We remark here that we are prioritizing the so-called "Min-Deletion" version of the 2-Lin(2) problem. We feel it is the more natural parameterization. For example, in the more traditional "Max-2-Lin(2)" formulation, the discrepancy between known algorithms and NP-hardness involves two quirky factors, 0.878 and 0.912. However, this disguises what we feel is the really interesting question—the same key open question that arises for the highly analogous Sparsest-Cut problem: Is there an efficient $(\varepsilon, O(\varepsilon))$-approximation, or even one that improves on the known $(\varepsilon, O(\sqrt{\log n})\varepsilon)$- and $(\varepsilon, O(\sqrt{\varepsilon}))$-approximations?

The relative importance of the "Min-Deletion" version is even more pronounced for the 2-Lin(q) problem. As we describe below, this version of the problem is essentially equivalent to the notorious Unique-Games problem. By way of contrast, the traditional maximization approximation factor measure for Unique-Games is not particularly interesting—it is known [11] that there is no constant-factor approximation for "Max-Unique-Games," but this appears to have no relevance for the Unique Games Conjecture.

1.1 History of the problem

No efficient $(\varepsilon, O(\varepsilon))$-approximation algorithm for 2-Lin(2) is known. The best known efficient approximation guarantee with no dependence on n dates back to the seminal work of Goemans and Williamson [13].

Theorem 1.1 (Goemans, Williamson). *There is a polynomial-time $(\varepsilon, (2/\pi)\sqrt{\varepsilon} + o(\varepsilon))$-approximation algorithm for* 2-Lin(2).

On the other hand, the best known approximation factor depending on n was given by Agarwal, Charikar, Makarychev, and Makarychev [1], building on the work of Arora, Rao, and Vazirani [4].

Theorem 1.2 (Agarwal et al.). *There is a polynomial-time factor-$O(\sqrt{\log n})$ approximation for* 2-Lin(2).

Generalizing Theorem 1.1 to 2-Lin(q), Charikar, Makarychev, and Makarychev [8] obtained the following result.

Theorem 1.3 (Charikar, Makarychev, Makarychev). *There is a polynomial-time $(\varepsilon, C_q\sqrt{\varepsilon})$-approximation for* 2-Lin(q) *(and indeed for* Unique-Games*), for a certain $C_q = \Theta(\sqrt{\log q})$.*

The question of whether or not this theorem can be improved is known to be essentially equivalent to the influential Unique Games Conjecture of Khot [17].

Theorem 1.4. *The Unique Games Conjecture implies ([18, 20]) that improving on Theorems 1.1, 1.3 is* NP*-hard. On the other hand ([22]), if there exists $q = q(\varepsilon)$ such that $(\varepsilon, \omega(\sqrt{\varepsilon}))$-approximating* 2-Lin$(q)$ *is* NP*-hard then the Unique Games Conjecture holds.*

The recent work of Arora, Barak, and Steurer [3] has also emphasized the importance of subexponential-time algorithms in this context.

Theorem 1.5 (Arora, Barak, Steurer). *For any $\beta \geq \log\log(n)/\log(n)$ there exists a $2^{O(qn^{\beta})}$-time algorithm for $(\varepsilon, O(\beta^{-3/2})\sqrt{\varepsilon})$-approximating* 2-Lin$(q)$. *For example, there is a constant $K < \infty$ and an $O(2^{n^{0.001}})$-time algorithm for $(\varepsilon, K\sqrt{\varepsilon})$-approximating* 2-Lin$(q)$ *for any $q = n^{o(1)}$.*

Finally, we remark that there is an *exact* algorithm for 2-Lin(2) running in time roughly 1.73^n due to Williams [25].

The known NP-hardness results for 2-Lin(q) are rather far from the bounds achieved by the known polynomial-time algorithms. It follows easily from the PCP Theorem that for any q, there exists $C > 1$ such that factor-C approximation of 2-Lin(q) is NP-hard. However, getting an explicit value for C has been a difficult task. In 1995, Bellare, Golreich, and Sudan [6] introduced the Long Code testing technique, which let them prove NP-hardness of approximating 2-Lin(2) to factor of roughly 1.02. Around 1997, Håstad [15] gave an optimal inapproximability result for the 3-Lin(2) problem; combining this with the "automated gadget" results of Trevisan et al. [24] allowed him to establish NP-hardness of factor-C approximation for any $C < 5/4$. By including the "outer PCP" results of Moshkovitz and Raz [19] we may state the following more precise theorem.

Theorem 1.6 (Håstad)**.** *Fix any $C < 5/4$. Then it is* NP*-hard to* $(\varepsilon, C\varepsilon)$*-approximate* 2-Lin$(2)$ *(for any $0 < \varepsilon \leq \varepsilon_0 = 1/4$). In fact ([19]), there is a reduction with quasilinear blowup; hence $(\varepsilon, C\varepsilon)$-approximation on size-$N$ instances requires $2^{N^{1-o(1)}}$ time assuming the Exponential-Time Hypothesis (ETH).*

Since 1997 there had been no improvement on this hardness factor of $5/4$, even for the (presumably much harder) 2-Lin(q) problem. We remark that Håstad [15] showed the same hardness result even for Max-Cut (albeit with a slightly smaller ε_0) and that O'Donnell and Wright [21] showed the same result for 2-Lin(q) (even with a slightly larger ε_0, namely $\varepsilon_0 \to 1/2$ as $q \to \infty$).

1.2 Our results and techniques

In this work we give the first known improvement to the factor-$5/4$ NP-hardness for 2-Lin(2) from [15]:

Theorem 1.7. *Fix any $C < 11/8$. Then it is* NP*-hard to* $(\varepsilon, C\varepsilon)$*-approximate* 2-Lin$(2)$ *(for any $0 < \varepsilon \leq \varepsilon_0 = 1/8$). Furthermore, the reduction takes* 3-Sat *instances of size n to* 2-Lin(2) *instances of size $O(n^8)$; hence $(\varepsilon, C\varepsilon)$-approximating* 2-Lin$(2)$ *instances of size N requires $2^{\Omega(N^{1/8})}$ time assuming the ETH.*

This theorem is proven in Section 3, wherein we also note that the same theorem holds in the special case of Max-Cut (albeit with some smaller, inexplicit value of ε_0).

Our result is a gadget reduction from the "7-ary Hadamard predicate" CSP, for which Chan [7] recently established an optimal NP-inapproximability result. In a sense our Theorem 1.7 is a direct generalization of Håstad's Theorem 1.6, which involved an optimal gadget reduction from the "3-ary Hadamard predicate" CSP, namely 3-Lin(2). That said, we should emphasize some obstacles that prevented this result from being obtained 15 years ago.

First, we employ Chan's recent approximation-resistance result for the 7-ary Hadamard predicate. In fact, what is crucial is not its approximation-resistance, but rather the stronger fact that it is a *useless* predicate, as defined in the recent work [5]. That is, given a nearly-satisfiable instance of the CSP, it is NP-hard to assign values to the variables so that the distribution on constraint 7-tuples is noticeably different from the uniform distribution.

Second, although in principle our reduction fits into the "automated gadget" framework of Trevisan et al. [24], in practice it is completely impossible to find the necessary gadget automatically, since it would involve solving a linear program with 2^{256} variables. Instead we had to construct and analyze our gadget by hand. On the other hand, by also constructing an appropriate LP dual solution, we are able to show the following in Section 4.

Theorem 1.8 (Informally stated)**.** *Our gadget achieving factor-$11/8$* NP*-hardness for* 2-Lin(2) *is* optimal *among gadget reductions from Chan's 7-ary Hadamard predicate hardness.*

(See Theorem 4.1 for a formal statement of this result.) In spite of Theorem 1.8, it seems extremely unlikely that factor-$11/8$ NP-hardness for 2-Lin(2) is the end of the line. Indeed, we view Theorem 1.7 as more of a "proof of concept" illustrating that the longstanding factor-$5/4$ barrier can be broken; we hope to see further improvements in the future. In particular, in Section 5 we present a candidate NP-hardness reduction from high-arity useless CSPs that we believe may yield NP-hardness of approximating 2-Lin(2) to any factor no larger than $3/2$. The analysis of this reduction eventually depends on a certain conjecture regarding analysis of Boolean functions that we were unable to resolve; thus we leave it as an open problem.

Finally, in Section 6 we show an inherent limitation of the method of gadget reductions from pairwise-independent predicates. We prove that such reductions can never establish an NP-hardness factor better than $1/(1-\mathrm{e}^{-1/2}) \approx 2.54$ for $(\varepsilon, C\varepsilon)$-approximation of 2-Lin(2). We believe that this highlights a serious bottleneck in obtaining an inapproximability result matching the performance of algorithms for this problem as most optimal NP-inapproximability results involve pairwise-independent predicates.

2 Preliminaries

Definition 2.1. Given $x, y \in \{-1,1\}^n$, the *Hamming distance* between x and y, denoted $d_H(x,y)$, is the number of coordinates i where x_i and y_i differ. Similarly, if $f, g : V \to \{-1,1\}$ are two functions over a variable set V, then the Hamming distance $d_H(f,g)$ between them is the number of inputs x where $f(x)$ and $g(x)$ disagree.

Definition 2.2. A *predicate* on n variables is a function $\phi : \{-1,1\}^n \to \{0,1\}$. We say that $x \in \{-1,1\}^n$ *satisfies* ϕ if $\phi(x) = 1$ and otherwise that it *violates* ϕ.

Definition 2.3. Given a predicate $\phi : \{-1,1\}^n \to \{0,1\}$, $\mathsf{Sat}(\phi)$ is the set of satisfying assignments.

Definition 2.4. A set $S \subseteq \{-1,1\}^n$ is a *balanced pairwise-independent subgroup* if it satisfies the following properties:

1. S forms a group under bitwise multiplication.
2. If x is selected from S uniformly at random, then $\Pr[x_i = 1] = \Pr[x_i = -1] = 1/2$ for any $i \in [n]$, and for any $i \neq j$, x_i and x_j are independent.

A predicate $\phi : \{-1,1\}^n \to \{0,1\}$ *contains a balanced pairwise-independent subgroup* if there exists a set $S \subseteq \mathsf{Sat}(\phi)$ which is a balanced pairwise-independent subgroup.

Definition 2.5. For a subset $S \subseteq [n]$, the parity function $\chi_S : \{-1,1\}^n \to \{-1,1\}$ is defined as

$$\chi_S(x) := \prod_{i \in S} x_i \,.$$

Definition 2.6. The Had_k predicate has $2^k - 1$ input variables, one for each nonempty subset $S \subseteq [k]$. The input string $\{x_S\}_{\emptyset \neq S \subseteq [k]}$ satisfies Had_k if for each S, $x_S = \chi_S\left(x_{\{1\}}, \cdots, x_{\{k\}}\right)$.

Fact 2.7. *The* Had_k *predicate contains a balanced pairwise-independent subgroup. (In fact, the whole set* $\mathsf{Sat}(\mathsf{Had}_k)$ *is a balanced pairwise-independent subgroup.)*

Given a predicate $\phi : \{-1,1\}^n \to \{0,1\}$, an instance $\mathcal{I}$ of the Max-ϕ CSP is a variable set V and a distribution of ϕ-constraints on these variables. To sample a constraint from this distribution, we write $\mathcal{C} \sim \mathcal{I}$, where $\mathcal{C} = ((x_1,b_1),(x_2,b_2),\ldots,(x_n,b_n))$. Here the x_i are in V and the b_i are in $\{-1,1\}$. An assignment $A : V \to \{-1,1\}$ satisfies the constraint $\mathcal{C}$ if

$$\phi\left(b_1 \cdot A(x_1), b_2 \cdot A(x_2), \ldots, b_n \cdot A(x_n)\right) = 1 \,.$$

We define several measures of assignments and instances.

Definition 2.8. The *value* of A on $\mathcal{I}$ is just $\mathsf{val}(A;\mathcal{I}) := \Pr_{\mathcal{C}\sim\mathcal{I}}[A \text{ satisfies } \mathcal{C}]$, and the value of the instance $\mathcal{I}$ is $\mathsf{val}(\mathcal{I}) := \max_{\text{assignments } A} \mathsf{val}(A;\mathcal{I})$. We define $\mathsf{uval}(A;\mathcal{I}) := 1 - \mathsf{val}(A;\mathcal{I})$ and similarly $\mathsf{uval}(\mathcal{I})$.

Definition 2.9. Let $(=) : \{-1,1\}^2 \to \{0,1\}$ be the equality predicate, i. e., for all $x_1, x_2 \in \{-1,1\}$, define $(=)(x_1,x_2) = 1$ iff $x_1 = x_2$. We will refer to the Max-$(=)$ CSP as the *Max*-2-Lin(2) CSP. Any constraint $\mathcal{C} = ((x_1,b_1),(x_2,b_2))$ in a Max-2-Lin(2) instance tests "$x_1 = x_2$" if $b_1 \cdot b_2 = 1$, and otherwise tests "$x_1 \neq x_2$."

Typically, a hardness of approximation result will show that given an instance $\mathcal{I}$ of the Max-ϕ problem, it is NP-hard to tell whether $\mathsf{val}(\mathcal{I}) \geq c$ or $\mathsf{val}(\mathcal{I}) \leq s$, for some numbers $c > s$. A stronger notion of hardness is *uselessness*, first defined in [5], in which in the second case, not only is $\mathsf{val}(\mathcal{I})$ small, but any assignment to the variables A appears "uniformly random" to the constraints. To make this formal, we will require a couple of definitions.

Definition 2.10. Given two probability distributions $\mathcal{D}_1$ and $\mathcal{D}_2$ on some set S, the total variation distance d_{TV} between them is defined to be

$$d_{TV}(\mathcal{D}_1,\mathcal{D}_2) := \sum_{e\in S} \frac{1}{2} \left|\mathcal{D}_1(e) - \mathcal{D}_2(e)\right| .$$

Definition 2.11. Given a Max-ϕ instance $\mathcal{I}$ and an assignment A, denote by $\mathcal{D}(A,\mathcal{I})$ the distribution on $\{-1,1\}^n$ generated by first sampling $((x_1,b_1),\ldots,(x_n,b_n)) \sim \mathcal{I}$ and then outputting $(b_1 \cdot A(x_1),\ldots,b_n \cdot A(x_n))$.

The work of Chan [7] showed uselessness for a wide range of predicates, including the Had_k predicate.

Theorem 2.12 (Chan)**.** *Let $\phi : \{-1,1\}^n \to \{0,1\}$ contain a balanced pairwise-independent subgroup. For every $\varepsilon > 0$, given an instance $\mathcal{I}$ of Max-ϕ, it is NP-hard to distinguish between the following two cases:*

- *(Completeness)* $\mathsf{val}(\mathcal{I}) \geq 1 - \varepsilon$.
- *(Soundness) For every assignment A, $d_{TV}(\mathcal{D}(A,\mathcal{I}),\mathcal{U}_n) \leq \varepsilon$, where $\mathcal{U}_n$ is the uniform distribution on $\{-1,1\}^n$.*

2.1 Gadgets

The work of Trevisan et al. [24] gives a generic methodology for constructing gadget reductions between two predicates. In this section, we review this with an eye towards our eventual Had_k-to-2-Lin(2) gadgets.

Suppose $\phi : \{-1,1\}^n \to \{0,1\}$ is a predicate one would like to reduce to another predicate $\psi : \{-1,1\}^m \to \{0,1\}$. Set $K := |\mathsf{Sat}(\phi)|$. We begin by arranging the elements of $\mathsf{Sat}(\phi)$ as the rows of a $K \times n$ matrix, which we will call the ϕ*-matrix*. An example of this is done for the Had_3 predicate in Figure 1. The columns of this matrix are elements of $\{-1,1\}^K$. Naming this set $V := \{-1,1\}^K$, we will think of V as the set of possible variables to be used in a gadget reduction from ϕ to ψ. One of the contributions of [24] was to show that the set V is sufficient for any such gadget reduction, and that any gadget reduction with more than 2^K variables has redundant variables which can be eliminated.

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & 1 & -1 & -1 & -1 \\ 1 & -1 & 1 & -1 & 1 & -1 & -1 \\ 1 & -1 & -1 & -1 & -1 & 1 & 1 \\ -1 & 1 & 1 & -1 & -1 & 1 & -1 \\ -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ -1 & -1 & -1 & 1 & 1 & 1 & -1 \end{bmatrix}$$

Figure 1: The Had_3-matrix. The rows are the satisfying assignments of Had_3.

Of these variables, the n variables found as the columns of the ϕ-matrix are special; they correspond to n of the variables in the original ϕ instance and are therefore called *generic primary* variables. We will call them $v_1, v_2, \ldots, v_n$, where they are ordered by their position in the ϕ-matrix. The remaining variables are called generic *auxiliary* variables. For example, per Figure 1, $(1,1,1,1,-1,-1,-1,-1)$ and $(1,-1,-1,1,-1,1,1,-1)$ are generic primary variables in any gadget reducing from ϕ, but the variable $(-1,-1,1,-1,1,-1,1,-1)$ is always a generic auxiliary variable.

On top of the variables V there will be a distribution of ψ constraints. As a result, a gadget $\mathcal{G}$ is just an instance of the Max-ψ CSP using the variable set V. As above, we will associate $\mathcal{G}$ with the distribution of ψ constraints and write $\mathcal{C} \sim \mathcal{G}$ to sample a constraint from this distribution.

Given an assignment $A : V \to \{0,1\}$, the goal is for $\mathcal{G}$ to be able to detect whether the values A assigns to the generic primary variables satisfy the ϕ predicate. For shorthand, we will say that *A satisfies ϕ* when

$$\phi\left(A(v_1), A(v_2), \ldots, A(v_n)\right) = 1 .$$

On the other hand, *A fails to satisfy ϕ* when this expression evaluates to 0. Of all assignments, we are perhaps most concerned with the *dictator* assignments. The i-th dictator assignment, written $d_i : \{-1,1\}^K \to \{-1,1\}$, is defined so that $d_i(x) = x_i$ for all $x \in \{-1,1\}^K$. The following fact shows why the dictator assignments are so important:

Fact 2.13. *Each dictator assignment d_i satisfies ϕ.*

Proof. The string $((v_1)_i, (v_2)_i, \ldots, (v_n)_i)$ is the i-th row of the ϕ-matrix, which, by definition, satisfies ϕ. $\square$

Before introducing the version we use in our reduction, we first give the standard definition of a gadget. Typically, one constructs a gadget so that the dictator assignments pass with high probability, whereas every assignment which fails to satisfy ϕ passes with low probability. This is formalized in the following definition, which is essentially from [24].

Definition 2.14 (Old definition)**.** A (c,s)-*generic gadget* reducing Max-ϕ to Max-ψ is a gadget $\mathcal{G}$ satisfying the following conditions.

- (Completeness) For every dictator assignment d_i, $\mathsf{uval}(d_i; \mathcal{G}) \leq c$.

- (Soundness) For any assignment A which fails to satisfy ϕ, $\mathsf{uval}(A;\mathcal{G}) \geq s$.

We use uval as our focus is on the deletion version of 2-Lin(2). We include the word *generic* in this definition to distinguish it from the specific type of gadget we will use to reduce Had_k to 2-Lin(2). See Section 2.3 for details.

This style of gadget reduction is appropriate for the case when one is reducing from a predicate for which one knows an inapproximability result and nothing else. However, in our case we are reducing from predicates containing a balanced pairwise-independent subgroup, and Chan [7] has shown *uselessness* for this class of predicates (see Theorem 2.12). As a result, we can relax the (Soundness) condition in Definition 2.14; when reducing from this class of predicates, it is sufficient to show that this (Soundness) condition holds for *distributions* of assignments which *appear random on the generic primary variables*. In the following paragraph we expand on what this means.

Denote by $\mathcal{A}$ a distribution over assignments A. The value of $\mathcal{A}$ is just the average value of an assignment drawn from $\mathcal{A}$, i. e., $\mathsf{val}(\mathcal{A};\mathcal{G}) := \mathbf{E}_{A\sim\mathcal{A}}\,\mathsf{val}(A;\mathcal{G})$, and similarly for $\mathsf{uval}(\mathcal{A};\mathcal{G})$. We say that $\mathcal{A}$ is *random on the generic primary variables* if the tuple

$$(A(v_1), A(v_2), \ldots, A(v_n))$$

is, over a random $A \sim \mathcal{A}$, distributed as a uniformly random element of $\{-1,1\}^n$.

Definition 2.15. Denote by $\mathsf{R}^{\mathrm{gen}}(\phi)$ the set of distributions which are *random on the generic primary variables*.

Our key definition is the following, which requires that our gadget only does well against distributions in $\mathsf{R}^{\mathrm{gen}}(\phi)$.

Definition 2.16 (New definition)**.** A (c,s)-*generic gadget* reducing Max-ϕ to Max-ψ is a gadget $\mathcal{G}$ satisfying the following properties:

- (Completeness) For every dictator assignment d_i, $\mathsf{uval}(d_i;\mathcal{G}) \leq c$.
- (Soundness) For any $\mathcal{A} \in \mathsf{R}^{\mathrm{gen}}(\phi)$, $\mathsf{uval}(\mathcal{A};\mathcal{G}) \geq s$.

The following proposition is standard, and we sketch its proof for completeness.

Proposition 2.17. *Suppose there exists a (c,s)-generic gadget reducing Max-ϕ to Max-ψ, where Max-ϕ is any predicate containing a balanced pairwise-independent subgroup. Then for all $\varepsilon > 0$, given an instance $\mathcal{I}'$ of Max-ψ, it is* NP*-hard to distinguish between the following two cases:*

- *(Completeness)* $\mathsf{uval}(\mathcal{I}') \leq c + \varepsilon$.
- *(Soundness)* $\mathsf{uval}(\mathcal{I}') \geq s - \varepsilon$.

Proof sketch. Let $\mathcal{I}$ be an instance of the Max-ϕ problem produced via Theorem 2.12. To dispense with some annoying technicalities, we will assume that every constraint $\mathcal{C} = ((x_1,b_1),\ldots,(x_n,b_n))$ in the support of $\mathcal{I}$ satisfies $b_i = 1$ for all $i = 1,\ldots,n$—if for some x_i we have $b_i = -1$, then we switch the sign of its corresponding primary variable in every ψ-constraint that contains x_i in the gadget for $\mathcal{C}$.

Construct an instance $\mathcal{I}'$ of Max-ψ as follows: for each constraint $\mathcal{C} = ((x_1,1),\ldots,(x_n,1))$ in the support of $\mathcal{I}$, add in a copy of $\mathcal{G}$—call it $\mathcal{G}_{\mathcal{C}}$—whose total weight is scaled down so that it equals the weight of $\mathcal{C}$. Further, identify the primary variables $v_1,\ldots,v_n$ of $\mathcal{G}_{\mathcal{C}}$ with the variables $x_1,\ldots,x_n$.

We now consider the completeness and soundness cases for Max-ϕ according to Theorem 2.12.

Completeness. In this case, the instance $\mathcal{I}$ is in the completeness case of Theorem 2.12, so there exists an assignment A to the variables of $\mathcal{I}$ which violates at most an ε-fraction of the constraints. We extend this to an assignment for all the variables of $\mathcal{I}'$ and show that it violates no more than a $(c+\varepsilon)$-fraction of the constraints. The extension is as follows: for any constraint $\mathcal{C} = ((x_1, 1), \ldots, (x_n, 1))$ which A satisfies, there is some dictator assignment to the variables of $\mathcal{G}_{\mathcal{C}}$ which agrees with A on the primary variables $v_1, \ldots, v_n$. Set A to also agree with this dictator assignment on the auxiliary variables in $\mathcal{G}_{\mathcal{C}}$. Regardless of how A is extended in the remaining gadgets $\mathcal{G}_{\mathcal{C}}$, it now labels a $(1-\varepsilon)$-fraction of the $\mathcal{G}$ gadgets in $\mathcal{I}'$ with a dictator assignment, meaning that $\mathsf{uval}(A; \mathcal{I}') \leq (1-\varepsilon) \cdot c + \varepsilon \cdot 1 \leq c + \varepsilon$.

Soundness. Let A be an assignment to the variables in $\mathcal{I}'$. We lower-bound the $\mathsf{uval}(A; \mathcal{I}')$ by roughly s assuming that $\mathcal{I}$ belongs to the soundness case of Theorem 2.12. Consider the distribution $\mathcal{A}$ of assignments to the gadget $\mathcal{G}$ generated as follows: sample $\mathcal{C} \sim \mathcal{I}$ and output the restriction of A to the variables of $\mathcal{G}_{\mathcal{C}}$. By the soundness case of Theorem 2.12, the distribution $(A(x_1), \ldots, A(x_n))$ is ε-close to uniform in total variation distance, and thus $\mathcal{A}$ is ε-close in total variation distance to some distribution $\mathcal{A}' \in \mathsf{R}^{\text{gen}}(\phi)$. As a result, by the definition of a (c,s)-generic gadget, we have $\mathsf{uval}(\mathcal{A}; \mathcal{G}) \geq \mathsf{uval}(\mathcal{A}'; \mathcal{G}) - \varepsilon \geq s - \varepsilon$. But then $\mathsf{uval}(\mathcal{A}; \mathcal{G}) = \mathsf{uval}(A; \mathcal{I}')$, which is therefore bounded below by $s - \varepsilon$.

By Theorem 2.12, it is NP-hard to distinguish between the two cases above for instance $\mathcal{I}$. It follows that distinguishing between $\mathsf{uval}(\mathcal{I}') \leq c + \varepsilon$ and $\mathsf{uval}(\mathcal{I}') \geq s - \varepsilon$ is NP-hard. □

2.2 Reducing into 2-Lin(2)

In this section, we consider gadgets which reduce into the 2-Lin(2) predicate. We show several convenient simplifying assumptions that can be made in this case.

Definition 2.18. An assignment $A : \{-1,1\}^K \to \{-1,1\}$ is *folded* if $A(x) = -A(-x)$ for all $x \in \{-1,1\}^K$. Here $-x$ is the bitwise negation of x. In addition, a distribution $\mathcal{A}$ is folded if every assignment in its support is folded.

The following proposition shows that when designing a gadget which reduces into 2-Lin(2), it suffices to ensure that its (Soundness) condition holds for folded distributions. The proof is standard.

Proposition 2.19. *For some predicate ϕ, suppose $\mathcal{G}$ is a gadget reducing Max-ϕ to Max-2-*Lin*(2) which satisfies the following two conditions:*

- *(Completeness) For every dictator assignment d_i,* $\mathsf{uval}(d_i; \mathcal{G}) \leq c$.
- *(Soundness) For any* folded $\mathcal{A} \in \mathsf{R}^{\text{gen}}(\phi)$, $\mathsf{uval}(\mathcal{A}; \mathcal{G}) \geq s$.

*Then there exists a (c,s)-generic gadget reducing Max-ϕ to Max-2-*Lin*(2).*

Remark 2.20. Here we are focusing on uval instead of val at the beginning of Section 2, so the c and s here corresponds to $1-c$ and $1-s$ there.

Proof. For each pair of antipodal points x and $-x$ in $\{-1,1\}^K$, pick one (say, x) arbitrarily, and set

$$\mathsf{canon}(x) := \mathsf{canon}(-x) := x.$$

This is the canonical variable associated to x and $-x$. The one constraint is that if either x or $-x$ is one of the generic primary variables, then it should be chosen as the canonical variable associated to x and $-x$. Define $\mathsf{is\text{-}canon}(x)$ to be 1 if $\mathsf{canon}(x) = x$ and (-1) otherwise. Now, let $\mathcal{G}'$ be the gadget whose constraints are sampled as follows:

1. Sample a constraint $A(x_1) \cdot A(x_2) = b$ from $\mathcal{G}$.
2. For $i \in \{1,2\}$, set $b_i = \mathsf{is\text{-}canon}(x_i)$.
3. Output the constraint $A(\mathsf{canon}(x_1)) \cdot A(\mathsf{canon}(x_2)) = b \cdot b_1 \cdot b_2$.

We claim that $\mathcal{G}'$ is a (c,s)-gadget reducing Max-ϕ to Max-2-Lin(2). Then the probability that an assignment A fails on $\mathcal{G}'$ is the same as the probability that the assignment $A'(x) := \mathsf{is\text{-}canon}(x) \cdot A(\mathsf{canon}(x))$ fails on $\mathcal{G}$. For any dictator function d_i, $d_i(x) = \mathsf{is\text{-}canon}(x) \cdot d_i(\mathsf{canon}(x))$ for all x. Therefore, d_i fails $\mathcal{G}'$ with probability c. Next, it is easy to see that for any assignment A, A' is folded and, due to our restriction on $\mathsf{canon}(\cdot)$, A' agrees with A on the generic primary variables. Thus, given a distribution $\mathcal{A} \in \mathsf{R}^{\text{gen}}(\phi)$, $\mathcal{A}$ fails on $\mathcal{G}'$ with the same probability that some folded distribution in $\mathsf{R}^{\text{gen}}(\phi)$ fails on $\mathcal{G}$, which is at least s. □

Proposition 2.21. *For fixed values of c and s, let $\mathcal{G}$ be a gadget satisfying the (Completeness) and (Soundness) conditions in the statement of Proposition 2.19. Then there exists another gadget satisfying these conditions which only uses equality constraints.*

Proof. Let $\mathcal{G}'$ be the gadget which replaces each constraint in $\mathcal{G}$ of the form $x \neq y$ with the constraint $x = -y$. If A is a folded assignment,

$$A(x) \neq A(y) \iff A(x) = A(-y)\,.$$

Thus, for every folded assignment A, $\mathsf{val}(A;\mathcal{G}) = \mathsf{val}(A,\mathcal{G}')$. As the (Completeness) and (Soundness) conditions in Proposition 2.19 only concern distributions over folded assignments, $\mathcal{G}'$ satisfies these conditions. □

This means that sampling from $\mathcal{G}$ can be written as $(x,y) \sim \mathcal{G}$, meaning that we have sampled the constraint "$x = y$."

2.3 The Had_k-to-2-Lin(2) gadget

Now we focus on our main setting, which is constructing a Had_k-to-2-Lin(2) gadget. Via Section 2.2, we only need to consider how well the gadget does against folded assignments.

The Had_k predicate has $2^k - 1$ variables. In addition, it has $K := 2^k$ satisfying assignments, one for each setting of the variables $x_{\{1\}}$ through $x_{\{k\}}$. It will often be convenient to take an alternative (but equivalent) viewpoint of the variable set $V := \{-1,1\}^K$ as the set of k-variable Boolean functions, i. e.,

$$V = \left\{ f \mid f : \{-1,1\}^k \to \{-1,1\} \right\}.$$

Remark 2.22. The variables 1^K and $(-1)^K$ in V correspond to the constant functions. In what follows, when considering *generic* Had_k-to-2-Lin(2) gadgets, it will be useful to view them as constants 1 and -1 in the 2-Lin(2) equations, instead of (auxiliary) variables. We argue that this is a valid simplification. Our result concerning Had_k-to-2-Lin(2) gadgets consists of two parts: constructing a Had_k-to-2-Lin(2) gadget in order to show NP-hardness result for Max-2-Lin(2), and prove that the gadget we constructed is optimal.

- For the first part, if we do a Had_k-to-2-Lin(2) reduction using these gadgets, the 2-Lin(2) instances we get may have constraints that involve constants, such as $(=)(x_1,-1)$. A standard transformation to turn them into ones that do not use constants is to introduce a global variable z, and replace 1 with z, -1 with $-z$. By changing the signs of all variables if necessary, we can always find an optimal assignment that gives z value 1. Thus the transformation maintains the values of the instances, and does not change the computational complexity of the problem.

- For the second part, observe that we always get gadgets at least as good by replacing the variable 1^K with constant 1 and $(-1)^K$ with constant -1. The constants coincide with the dictator assignments for 1^K and $(-1)^K$, so the completeness value does not change, and the soundness does not decrease after this simplification.

The Had_k matrix is a $2^k \times (2^k-1)$ matrix whose rows are indexed by strings in $\{-1,1\}^k$ and whose columns are indexed by nonempty subsets $S \subseteq [k]$. The (x,S)-entry of this matrix is $\chi_S(x)$. This can be verified by noting that for any $x \in \{-1,1\}^k$,

$$\big(\chi_{\{1\}}(x), \chi_{\{2\}}(x), \ldots, \chi_{\{k\}}(x), \chi_{\{1,2\}}(x), \ldots, \chi_{\{1,2,\ldots,k\}}(x)\big)$$

is a satisfying assignment of the Had_k predicate. As a result, for each $S \neq \emptyset$, χ_S is a column in the Had_k matrix. Therefore, these functions are the generic primary variables. However, it will be convenient to consider a larger set of functions to be primary. For example, because we plan on using our gadget on folded assignments, χ_S and $-\chi_S$ will always have opposite values, and so the $-\chi_S$ should also be primary variables. In addition, it is a little unnatural to have every parity function but one as a primary variable, so we will include the constant function $\chi_\emptyset$ and its negation $-\chi_\emptyset$ in the set of primary variables. In total, we have the following definition. Note that in contrast to the above discussion about generic gadgets, we include the constant functions as variables in the following definition of Had_k-to-2-Lin(2) gadgets.

Definition 2.23. The variables of a Had_k-to-2-Lin(2) gadget are all Boolean functions over k variables. The *primary variables* of a Had_k-to-2-Lin(2) gadget are the functions $\pm\chi_S$, for any $S \subseteq [k]$. The remaining functions are auxiliary variables.

To account for the inclusion of $\chi_\emptyset$ as a primary variable, we will have to modify some of our definitions from Section 2.1. We begin by defining the following modification to the Had_k predicate, and we now refer to the definition at the beginning of this subsection as Had'_k.

Definition 2.24. The Had_k predicate has 2^k input variables, one for each subset $S \subseteq [k]$. The input string $\{x_S\}_{S\subseteq[k]}$ satisfies Had_k if for each $S \neq \emptyset$, $x_S = x_\emptyset \cdot \prod_{i\in S}(x_\emptyset \cdot x_{\{i\}})$.

In other words, if $x_\emptyset = 1$, then the remaining variables should satisfy the Had'_k predicate, and if $x_\emptyset = -1$, then their negations should. We will say that A *satisfies the* Had_k *predicate* if

$$\mathsf{Had}_k\left(A\left(\chi_\emptyset\right), A\left(\chi_{\{1\}}\right), \ldots, A\left(\chi_{\{k\}}\right), A\left(\chi_{\{1,2\}}\right), \ldots, A\left(\chi_{[k]}\right)\right) = 1\,.$$

Otherwise, A *fails to satisfy the* Had_k *predicate*. We say that $\mathcal{A}$ is *random on the primary variables* if the tuple

$$\left(A\left(\chi_\emptyset\right), A\left(\chi_{\{1\}}\right), \ldots, A\left(\chi_{\{k\}}\right), A\left(\chi_{\{1,2\}}\right), \ldots, A\left(\chi_{[k]}\right)\right)$$

is, over a random $A \sim \mathcal{A}$, distributed as a uniformly random element of $\{-1,1\}^K$.

Definition 2.25. Denote by $\mathsf{R}(\mathsf{Had}_k)$ the set of folded distributions which are *random on the variables* $\{\chi_S\}_{S\subseteq[k]}$.

Definition 2.26. A (c,s)-*gadget* reducing Max-Had_k to Max-2-Lin(2) is a gadget $\mathcal{G}$ satisfying the following properties:

- (Completeness) For every dictator and negated dictator assignment $\pm d_i$, $\mathsf{uval}(\pm d_i; \mathcal{G}) \le c$.
- (Soundness) For any $\mathcal{A} \in \mathsf{R}(\mathsf{Had}_k)$, $\mathsf{uval}(\mathcal{A}; \mathcal{G}) \ge s$.

Proposition 2.27. *The following two statements are equivalent:*

1. *There exists a (c,s)-gadget reducing Max-Had_k to Max-2-Lin(2).*
2. *There exists a (c,s)-generic gadget reducing Max-Had'_k to Max-2-Lin(2).*

Proof. We prove the two directions separately. Recall that the gadgets in both cases are distributions of 2-Lin(2) constraints over essentially the same set of variables, except that in (1) we have variables $\pm\chi_\emptyset$, whereas in (2), we have constants ± 1. To convert a gadget $\mathcal{G}$ in (1) to $\mathcal{G}'$ in (2), we simply replace $\pm\chi_\emptyset$ with ± 1, and vice versa.

(1) $\Rightarrow$ (2). Let $\mathcal{G}$ be a (c,s)-gadget reducing Max-Had_k to Max-2-Lin(2), and $\mathcal{G}'$ the corresponding (c,s)-generic gadget $\mathcal{G}'$ reducing Max-Had'_k to Max-2-Lin(2). We claim that for any folded $\mathcal{A}' \in \mathsf{R}^{\text{gen}}(\mathsf{Had}'_k)$, $\mathsf{uval}(\mathcal{A}'; \mathcal{G}') \ge s$. To see this, construct distribution $\mathcal{A} \in \mathsf{R}(\mathsf{Had}_k)$ as follows: sample $A' \sim \mathcal{A}'$ and $b \sim \{-1,1\}$, output the assignment A where we assign $A(\chi_\emptyset) = b$, $A(-\chi_\emptyset) = -b$, and $A(f) = bA'(f)$ for all $f \notin \{\pm\chi_\emptyset\}$. By definition of $\mathsf{R}^{\text{gen}}(\mathsf{Had}'_k)$, we have that A' is uniformly random on $\{\chi_S\}_{S\neq\emptyset}$, and since b is uniform and independently sampled, we have that $\mathcal{A} \in \mathsf{R}(\mathsf{Had}_k)$ and therefore $\mathsf{uval}(\mathcal{A}; \mathcal{G}) \ge s$. We also have $A(f)A(\chi_\emptyset) = A'(f)\cdot 1$ and $A(f)A(g) = A'(f)A'(g)$ for $f,g \notin \{\pm\chi_\emptyset\}$, so $\mathsf{uval}(\mathcal{A}'; \mathcal{G}') = \mathsf{uval}(\mathcal{A}; \mathcal{G})$. As a result, $\mathcal{G}'$ satisfies the (Completeness) and (Soundness) conditions in the statement of Proposition 2.19, meaning it is a (c,s)-generic gadget reducing Max-Had'_k to Max-2-Lin(2).

(2) $\Rightarrow$ (1). Let $\mathcal{G}'$ be a (c,s)-*generic* gadget reducing Max-Had'_k to Max-2-Lin(2), and $\mathcal{G}$ be the corresponding (c,s)-gadget reducing Max-Had_k to Max-2-Lin(2). Let $\mathcal{A} \in \mathsf{R}(\mathsf{Had}_k)$, and for $b \in \{-1,1\}$, write $\mathcal{A}_{(b)}$ for $\mathcal{A}$ conditioned on the variable $\chi_\emptyset$ being assigned the value b. Then $b\cdot\mathcal{A}_{(b)}$ (by which we mean the distribution where we sample $A \sim \mathcal{A}_{(b)}$ and output $b\cdot A$) is in $\mathsf{R}^{\text{gen}}(\mathsf{Had}'_k)$ for both $b \in \{-1,1\}$, and so $\mathsf{uval}(b\cdot\mathcal{A}_{(b)}; \mathcal{G}) = \mathsf{uval}\left(b\cdot\mathcal{A}_{(b)}; \mathcal{G}'\right) \ge s$. As $\mathsf{uval}(\mathcal{A}_{(b)}; \mathcal{G}) = \mathsf{uval}\left(b\cdot\mathcal{A}_{(b)}; \mathcal{G}\right)$, $\mathsf{uval}(\mathcal{A}; \mathcal{G}) \ge s$, and so $\mathcal{G}$ is a (c,s)-gadget reducing Max-Had_k to Max-2-Lin(2). $\square$

Combining this with Proposition 2.17, we have the following corollary.

Corollary 2.28. *Suppose there exists a* (c,s)*-gadget reducing Max-*Had_k *to Max-*$2\text{-Lin}(2)$*. Then for all* $\varepsilon > 0$*, given an instance* $\mathcal{I}$ *of Max-*$2\text{-Lin}(2)$*, it is* NP*-hard to distinguish between the following two cases:*

- *(Completeness)* $\mathsf{uval}(\mathcal{I}) \le c + \varepsilon$.
- *(Soundness)* $\mathsf{uval}(\mathcal{I}) \ge s - \varepsilon$.

2.4 Reducing to the length-one case

When constructing good gadgets, we generally want dictators to pass with as high of probability as possible. By Proposition 2.21, we can assume that our gadget operates by sampling an edge (x,y) and testing equality between the two endpoints. Any such edge of Hamming distance i will be violated by i/K of the dictator assignments. Intuitively, then, if we want dictators to pass with high probability, we should concentrate the probability mass of our gadget $\mathcal{G}$ on edges of low Hamming distance. The following proposition shows that this is true in the extreme: so long as we are only concerned with maximizing the quantity s/c, we can always assume that $\mathcal{G}$ is entirely supported on edges of Hamming distance one.

Proposition 2.29. *Suppose there exists a* (c,s)*-gadget* $\mathcal{G}$ *reducing Max-*Had_k *to Max-*$2\text{-Lin}(2)$*. Then there exists a* (c',s')*-gadget reducing Max-*Had_k *to Max-*$2\text{-Lin}(2)$ *using only length-one edges for which*

$$\frac{s'}{c'} \ge \frac{s}{c}\,.$$

Proof. For each $i \in \{1,\dots,K\}$, let p_i be the probability that an edge sampled from $\mathcal{G}$ has length i, and let $\mathcal{G}_i$ denote the distribution of $\mathcal{G}$ conditioned on this event. Then sampling from $\mathcal{G}$ is equivalent to first sampling a length i with probability p_i, and then sampling an edge from $\mathcal{G}_i$.

Let $Q = 1\cdot p_1 + 2\cdot p_2 + \cdots + K\cdot p_K$, and for each $i \in \{1,\dots,K\}$ define $q_i = i\cdot p_i/Q$. It is easy to see that the q_i form a probability distribution. Now we may define the new gadget $\mathcal{G}'$ as follows:

1. Sample a length i with probability q_i.
2. Sample $(x,y) \sim \mathcal{G}_i$.
3. Pick an arbitrary shortest path $x = x_0, x_1, \dots, x_i = y$ through the hypercube $\{-1,1\}^K$.
4. Output a uniformly random edge (x_j, x_{j+1}) from this path.

Note that $\mathcal{G}'$ only uses length-one edges. Let $\mathcal{G}'_i$ denote the distribution of $\mathcal{G}'$ conditioned on i being sampled in the first step. (Note that $\mathcal{G}'_i$ is defined in a way that is different from the way $\mathcal{G}_i$ is defined.)

Let $A : \{-1,1\}^K \to \{-1,1\}$ be any assignment. Then

$$\mathsf{uval}(A;\mathcal{G}) = \sum_{i=1}^{K} p_i \cdot \mathsf{uval}(A;\mathcal{G}_i)\,, \qquad \text{and} \qquad \mathsf{uval}(A;\mathcal{G}') = \sum_{i=1}^{K} q_i \cdot \mathsf{uval}(A;\mathcal{G}'_i)\,.$$

We can relate $\mathsf{uval}(A;\mathcal{G}'_i)$ to $\mathsf{uval}(A;\mathcal{G}_i)$ as follows: if A assigns different values to the endpoints of the edge $(x,y) \sim \mathcal{G}$, then on any shortest path $x = x_0, x_1, \dots, x_i = y$ through the hypercube $\{-1,1\}^K$, A must assign different values to at least one of the edges (x_j, x_{j+1}). As a result, every time A errs on $\mathcal{G}_i$, it must err at least a $(1/i)$-fraction of the time on $\mathcal{G}_i'$. This means that:

$$\mathsf{uval}(A;\mathcal{G}_i') \geq \frac{\mathsf{uval}(A;\mathcal{G}_i)}{i}. \tag{2.1}$$

In the case when A is a dictator function, Equation (2.1) becomes an equality. This is because $x = x_0, x_1, \ldots, x_i = y$ is a shortest path between x and y through the hypercube $\{-1,1\}^K$. If A assigns the same values to x and y, then it will assign the same values to all of $x_0, x_1, \ldots, x_i$. If, on the other hand, it assigns different values to x and y, then it will assign different values to the endpoints of exactly one edge (x_j, x_{j+1}).

Now we can use this to relate $\mathsf{uval}(A;\mathcal{G}')$ to $\mathsf{uval}(A;\mathcal{G})$:

$$\begin{aligned}
\mathsf{uval}(A;\mathcal{G}') &= \sum_{i=1}^{K} q_i \cdot \mathsf{uval}(A;\mathcal{G}_i') \\
&\geq \sum_{i=1}^{K} \left(\frac{i \cdot p_i}{Q}\right) \cdot \frac{\mathsf{uval}(A;\mathcal{G}_i)}{i} \\
&= \frac{1}{Q} \sum_{i=1}^{K} p_i \cdot \mathsf{uval}(A;\mathcal{G}_i) \\
&= \frac{1}{Q} \mathsf{uval}(A;\mathcal{G}). \qquad (2.2)
\end{aligned}$$

Here the inequality follows from the definition of q_i and Equation (2.1). As Equation (2.1) is an equality in the case when A is a dictator function, we have that $\mathsf{uval}(A;\mathcal{G}') = (1/Q)\mathsf{uval}(A;\mathcal{G})$ in this case.

Let $\mathcal{A} \in \mathsf{R}(\mathsf{Had}_k)$ maximize $\mathsf{val}(\mathcal{A};\mathcal{G}')$, and let d_i be any dictator function. Then

$$\frac{s'}{c'} = \frac{\mathsf{uval}(\mathcal{A};\mathcal{G}')}{\mathsf{uval}(d_i;\mathcal{G}')} \geq \frac{\frac{1}{Q}\mathsf{uval}(\mathcal{A};\mathcal{G})}{\frac{1}{Q}\mathsf{uval}(d_i;\mathcal{G})} = \frac{\mathsf{uval}(\mathcal{A};\mathcal{G})}{\mathsf{uval}(d_i;\mathcal{G})} \geq \frac{s}{c}.$$

Here the first inequality is by Equation (2.2) (and the fact that it is an equality for dictators), and the second inequality follows from the fact that $\mathsf{uval}(\mathcal{A},\mathcal{G}) \geq s$ and $\mathsf{uval}(d_i,\mathcal{G}) = c$. □

2.5 Linear programs

One of the key insights of the paper [24] is that optimal gadgets (as per Definition 2.14) can be computed by simply solving a linear program. Fortunately, the same holds for computing optimal gadgets as per Definition 2.26. In our case, the appropriate linear program (taking into account Proposition 2.29) is:

$$\begin{aligned}
\max \quad & s \\
\text{s.t.} \quad & \mathsf{uval}(\mathcal{A};\mathcal{G}) \geq s, \quad \forall \mathcal{A} \in \mathsf{R}(\mathsf{Had}_k), \\
& \mathcal{G} \text{ is a gadget supported on edges of length one.}
\end{aligned}$$

As written, this linear program has an (uncountably) infinite number of constraints, but this can fixed by suitably discretizing the set $\mathsf{R}(\mathsf{Had}_k)$. This is not so important for us, as even after performing this step, the linear program is simply too large to ever be feasible in practice. What is important for us is that we can take its dual; doing so yields the following linear program.

Definition 2.30. The *dual LP* is defined as

$$\begin{aligned} \min \quad & s \\ \text{s.t.} \quad & \Pr_{A \sim \mathcal{A}}[A(x) = A(y)] \le s, \quad \forall \text{ edges } (x,y) \text{ of length one}, \\ & \mathcal{A} \in \mathsf{R}(\mathsf{Had}_k)\,. \end{aligned}$$

The dual linear program shows us that we can upper-bound the soundness of any gadget with the value s by exhibiting a distribution on assignments in $\mathsf{R}(\mathsf{Had}_k)$ which passes each length-one edge with probability at least s. Moreover, strong LP duality tells us that the optimum values of the two LPs are the same. Hence, we can prove a *tight* upper bound by exhibiting the right distribution. We do this in Section 4 for gadgets reducing Max-Had_3 to Max-2-Lin(2).

2.6 The Had_3 gadget

In this section, we will prove some structural results about the hypercube $\{-1,1\}^8$ which are relevant to any Had_3-to-2-Lin(2) gadget. The results of this section will be useful for both Sections 3 and 4.

Given a string $x \in \{-1,1\}^n$ and subset of strings $B \subseteq \{-1,1\}^n$, we define the distance of x to B as $d_H(x,B) := \min_{y \in B} d_H(x,y)$.

Let $V = \{-1,1\}^8$, and let $G = (V,E)$ be the hypercube graph, where we connect two vertices $v_1, v_2 \in \{-1,1\}^8$ with an edge if and only if $d_H(v_1,v_2) = 1$.

Definition 2.31. Given a hypercube graph $G = (V,E)$, where $V = \{-1,1\}^8$. Let V_0 be the set of primary variables of a gadget from Had_3, and for any $i > 0$, define $V_i = \{x \in V \mid d_H(x,V_0) = i\}$. This gives a partition of vertices in V according to their distances to V_0.

We can identify V with the set of 3-variable Boolean functions. The set of primary variables V_0 corresponds to the set of affine functions, i. e., those of the form $\pm\chi_S$, where $S \subseteq [3]$.

Proposition 2.32. *For the hypercube graph $G = (V,E)$, where $V = \{-1,1\}^8$, the following holds:*

1. *The vertex set V can be partitioned as $V = V_0 \cup V_1 \cup V_2$, $|V_0| = 16$, $|V_1| = 128$, and $|V_2| = 112$.*
2. *Each $x \in V_0$ has eight neighbors in V_1.*
3. *Let $f, g \in V_0$ be a pair of distinct functions. Then either $d_H(f,g) = 8$, or $d_H(f,g) = 4$.*
4. *For any $x, y \in \{-1,1\}^3$, $x \neq y$, $b_x, b_y \in \{-1,1\}$, the number of functions $f \in V_0$ such that $f(x) = b_x$ is 8, and the number of functions $f \in V_0$ such that $f(x) = b_x$ and $f(y) = b_y$ is 4.*
5. *Each $x \in V_1$ has one neighbor in V_0 and seven neighbors in V_2.*
6. *Each $x \in V_2$ has eight neighbors in V_1. Further more, these eight neighbors in V_1 can be grouped into 4 pairs, and the two vertices in each pair share a common neighbor in V_0. This gives exactly 4 vertices in V_0 that are Hamming distance 2 away from x.*

7. *Let $f \in V_2$, and let g_1, g_2, g_3, and g_4 be the four vertices in V_0 which are Hamming distance 2 away from f. Then for any $x \in \{-1,1\}^3$, three of the g_i functions have the same value and one has a different value, and therefore $f(x) = \mathsf{sign}(g_1(x)+g_2(x)+g_3(x)+g_4(x))$. We say that g_1, g_2, g_3 and g_4 are* the primary variables associated with f.

Proof. In this proof, we will take the viewpoint of V as the set of 3-variable Boolean functions.

Item (2) is straightforward—for each function $f \in V_0$, changing any of the 8 positions would result in a function in V_1 by definition, and since functions in V_0 are at distance at least 4 from each other, their sets of neighbors in V_1 do not intersect.

For item (3), suppose we have $f = b_f \chi_F$ and $g = b_g \chi_G$. If $F = G$, then since $f \neq g$ we must have $f = -g$, so $d_H(f,g) = 8$. Otherwise, since $F \neq G$,

$$\mathop{\mathbf{E}}_{x}[f(x)g(x)] = \mathop{\mathbf{E}}_{x\sim\{-1,1\}^3}[b_f b_g \chi_F(x)\chi_G(x)] = 0\,,$$

where x is sampled uniformly over $\{-1,1\}^3$. Thus in this case $d_H(f,g) = 4$.

We prove item (4) by a dimension argument. A function $f \in V_0$ can be defined as $f(x_1,x_2,x_3) = (-1)^{b_0+b_1x_1+b_2x_2+b_3x_3}$, and we can specify f by giving the parameters b_0, b_1, b_2 and b_3. Specifying the value of f at a single point imposes 1 affine relation on the 4 parameters, so the number of affine functions that satisfies this constraint is $2^{4-1} = 8$. Specifying the values at 2 different points introduces 2 *independent* affine relations and thus the resulting number of affine functions becomes $2^{4-2} = 4$.

We now prove the remaining items. The primary variables are of the form $\pm\chi_S$, where $S \subseteq [3]$. There are 16 such functions, and so $|V_0| = 16$.

Let f' differ from one of the primary variables on a single input. It must be at least distance 3 from any of the other primary variables. This means that all its neighbors are at distance 2 or 4 from all affine functions and thus are all in $V \setminus V_0 \setminus V_1$. There are $16 \cdot 8 = 128$ distinct ways of constructng such an f', and so $|V_1| = 128$.

This leaves $256 - 16 - 128 = 112$ variables in V not yet accounted for. We will now show a method for constructing exactly 112 different elements of V_2; by the pigeonhole principle, this shows that V can be partitioned as in item (1) with the given sizes. Item (5) also follows because each function in V_1 has 8 neighbors, and exactly one of them is in V_0. Items (6) and (7) follow naturally from the proof below.

Given three primary variables $b_1\chi_{S_1}$, $b_2\chi_{S_2}$, and $b_3\chi_{S_3}$, where $b_1,b_2,b_3 \in \{-1,1\}$, set $b_4 := -b_1 \cdot b_2 \cdot b_3$ and $S_4 := S_1 \Delta S_2 \Delta S_3$. Consider the function f defined as

$$f(x) := \mathsf{sign}\left(b_1\chi_{S_1}(x) + b_2\chi_{S_2}(x) + b_3\chi_{S_3}(x) + b_4\chi_{S_4}(x)\right)\,.$$

To see that this $\mathsf{sign}(\cdot)$ is well-defined, note that by definition, $\prod_{i=1}^4 b_i\chi_{S_i}(x) = -1$ for all $x \in \{-1,1\}^3$. As a result, for any x, three of the $b_i\chi_{S_i}(x)$ have the same value, while the other one has a different value. This also means that for all x, we have

$$\sum_{i=1}^4 b_i\chi_{S_i}(x) = 2\cdot\mathsf{sign}\left(\sum_{i=1}^4 b_i\chi_{S_i}(x)\right)\,.$$

Thus, the correlation of any of the variables $b_i\chi_{S_i}$ with f is

$$\mathop{\mathbf{E}}_{x}[f(x)\cdot b_i\chi_{S_i}] = \frac{1}{2}\mathop{\mathbf{E}}_{x}\left[\left(\sum_{i=1}^4 b_i\chi_{S_i}(x)\right)\cdot b_i\chi_{S_i}\right] = \frac{1}{2}\,.$$

In other words, $\Pr_x[f(x) = b_i \chi_{S_i}] = 3/4$ for each $i \in \{1, \dots, 4\}$. This is equivalent to saying that f is at distance 2 from each of the $b_i \chi_{S_i}$, for $i = 1, 2, 3, 4$.

There are $2^3 \cdot \binom{8}{3} = 448$ ways of selecting the $b_i \chi_{S_i}$ for $i = 1, 2, 3$, and there are 4 different choices of $b_1 \chi_{S_1}$, $b_2 \chi_{S_2}$ and $b_3 \chi_{S_3}$ that lead to the same function. Therefore this construction gives 112 unique functions in V_2. As there are only 112 functions in V which are in neither V_0 nor V_1, all of the remaining variables in V must be contained in V_2, and they must all be generated in the manner above.

Now we consider the neighbors of $f \in V_2$. To get from f to each of its 4 associated functions in V_0, we need to flip 2 bits. Since we can flip them in 2 different orders, this gives all 8 neighbors of f and they are all in V_1. $\square$

Proposition 2.33. *Let $B = \mathsf{sat}(\mathsf{Had}_3)$. Then*

$$\Pr_x[d_H(x,B) = 0] = \frac{1}{16}, \quad \Pr_x[d_H(x,B) = 1] = \frac{1}{2}, \quad \textit{and} \quad \Pr_x[d_H(x,B) = 2] = \frac{7}{16},$$

where x is a uniformly random element of $\{-1,1\}^8$.

Proof. This can be proven using a proof similar to Proposition 2.32. Alternatively, we can just show a direct correspondence between the setting here and the setting in Proposition 2.32, as follows.

The input to Had_3 is a set of bits $\{x_S\}_{S \subseteq [k]}$, which can also be thought of as the function $f : \mathcal{P}(\{1,2,3\}) \to \{-1,1\}$ in which $f(S) := x_S$. The satisfying assignments are then any function of the form $S \mapsto b \cdot \chi_S(x)$, where $b \in \{-1,1\}$ and $x \in \{-1,1\}^3$ are both fixed. For a string $x \in \{-1,1\}^3$, let $\alpha(x)$ be the corresponding set, i. e., $\alpha(S)_i = -1$ if and only if $i \in S$. For any function $f : \mathcal{P}(\{1,2,3\}) \to \{-1,1\}$, we can associate it with the function $\alpha(f) : \{-1,1\}^3 \to \{-1,1\}$ defined by $\alpha(f)(x) := f(\alpha(x))$ for all x. Then α maps any satisfying assignment to Had_3 into one of the primary variables in V_0, and more generally, $d_H(f,B) = i$ if and only if $\alpha(f) \in V_i$. The proposition therefore follows by applying Proposition 2.32 and by noting that $16/256 = 1/16$, $128/256 = 1/2$, and $112/256 = 7/16$. $\square$

2.7 Reducing to Max-Cut

Definition 2.34. Let $(\neq) : \{-1,1\}^2 \to \{0,1\}$ be the inequality predicate, i. e., for all $x_1, x_2 \in \{-1,1\}$, $(\neq)(x_1,x_2) = 1$ iff $x_1 \neq x_2$. The Max-Cut CSP is the special case of the Max-$(\neq)$ CSP in which every constraint $\mathcal{C} = ((x_1,b_1),(x_2,b_2))$ satisfies $b_1 = b_2 = 1$. In other words, every constraint is of the form "$x_1 \neq x_2$."

Proposition 2.35. *For some predicate ϕ, suppose $\mathcal{G}$ is (c,s)-generic gadget reducing Max-ϕ to Max-*2-Lin(2). *Then there exists a (c',s')-gadget reducing Max-ϕ to* Max-Cut *satisfying*

$$\frac{s'}{c'} = \frac{s}{c}.$$

Proof. Suppose the vertex set of $\mathcal{G}$ is $V = \{-1,1\}^K$. Let $\mathcal{G}'$ be the gadget which operates as follows:

1. With probability $1 - 1/2^K$, pick $x \in \{-1,1\}^K$ and output the constraint "$x \neq -x$."
2. Otherwise, sample $\mathcal{C} \sim \mathcal{G}$. If $\mathcal{C}$ is of the form "$x \neq y$," output "$x \neq y$." If $\mathcal{C}'$ is of the form "$x = y$," output "$x \neq -y$."

Any folded assignment A fails $\mathcal{G}'$ with probability at most $1/2^K$. Any assignment A which is *not* folded fails $\mathcal{G}'$ with probability at least

$$\left(1-\frac{1}{2^K}\right)\cdot\frac{2}{2^K} > \frac{1}{2^K}\,.$$

As a result, we can always assume that any assignment is folded.

Now, if A is folded, then for any $x,y \in \{-1,1\}^K$, $A(x) = A(y)$ if and only if $A(x) \neq A(-y)$. As a result, $\mathsf{uval}(A;\mathcal{G}') = \mathsf{uval}(A;\mathcal{G})/2^K$. Thus, $c' = c/2^K$, $s' = s/2^K$, and so $s'/c' = s/c$. □

3 The factor-$11/8$ hardness result

In this section, we prove the following theorem.

Theorem 3.1. *There is a* $(1/8, 11/64)$*-gadget reducing* Had_3 *to* 2-Lin(2).

Using Propositions 2.17 and 2.35, we have the following two corollaries.

Corollary 3.2. *There is a* (c,s)*-generic gadget reducing* Had_3 *to* Max-Cut *with* $s/c = 11/8$.

Corollary 3.3 (Theorem 1.7 restated)**.** *Fix any* $C < 11/8$. *Then it is* NP*-hard to achieve a factor-*C *approximation for both the Max-*2-Lin(2) *and the* Max-Cut *CSPs.*

Proof of Theorem 3.1. To construct our gadget, we will assign a nonnegative weight to each edge in the gadget. Our gadget will then sample each edge with probability equal to its weight normalized by the weight of the entire gadget. As argued in Proposition 2.29, our gadget will only use length-one edges. And by Proposition 2.21, our gadget will only use equality constraints. For $f,g \in V$ with $d_H(f,g) = 1$, the weight of the edge $\{f,g\}$ is 5 if and only if either $f \in V_0$ or $g \in V_0$, and otherwise the weight is 1. The total weight of the edges in $\mathcal{G}$ is $5 \times 128 + 896 = 1536$.

For the completeness, the fact that the dictators pass with probability $7/8$ follows immediately from the fact that $\mathcal{G}$ only uses edges of length one. For the soundness, let $\mathcal{A} \in \mathsf{R}(\mathsf{Had}_3)$. We consider each A in the support of $\mathcal{A}$, i. e., all folded assignments. We apply one of the following three lemmas lower-bounding $\mathsf{uval}(A;\mathcal{G})$ depending on the distance between the assignment to the primary variables to A and the satisfying assignments of Had_3.

Lemma 3.4. *Let* $A : \{-1,1\}^8 \to \{-1,1\}$. *If the assignment of* A *to the primary variables satisfies the* Had_3 *predicate, then* $\mathsf{uval}(A;\mathcal{G}) \geq 1/8$.

Lemma 3.5. *Let* $A : \{-1,1\}^8 \to \{-1,1\}$. *If the assignment of* A *to the primary variables is distance one from satisfying the* Had_3 *predicate, then* $\mathsf{uval}(A;\mathcal{G}) \geq 21/128$.

Lemma 3.6. *Let* $A : \{-1,1\}^8 \to \{-1,1\}$. *If the assignment of* A *to the primary variables is distance two from satisfying the* Had_3 *predicate, then* $\mathsf{uval}(A;\mathcal{G}) \geq 3/16$.

Proposition 2.33 gives the probability that a random $A \sim \mathcal{A}$ will fall into each of these three cases. In total

$$\mathsf{uval}(\mathcal{A};\mathcal{G}) \geq \frac{1}{16}\cdot\frac{1}{8} + \frac{1}{2}\cdot\frac{21}{128} + \frac{7}{16}\cdot\frac{3}{16} = \frac{11}{64}\,,$$

which is what the theorem guarantees.

Before proving these lemmas, we will do some preliminary work which is relevant to all three. In the remaining part of this section, let A be some partial assignment to variables in V. We focus on partial assignments that at least assign values to all primary variables. To analyze the quality of the gadget, we analyze certain measures of the gadget and bound the best possible way to complete A to a full assignment. All definitions in the rest of this section will be with respect to the partial assignment A.

We classify variables in V_2 by the assignments of their associated affine functions, where association is defined in item (7) of Proposition 2.32.

Definition 3.7. Let A be a partial assignment, and $f \in V_2$ be a function associated with $g_0, g_1, g_2, g_3 \in V_0$. We say that f is a $(4,0)$ function if $A(g_0) = A(g_1) = A(g_2) = A(g_3)$. We define $(3,1)$ and $(2,2)$ functions similarly.

We consider paths of length 2 that start at some $f \in V_2$ and end at one of the affine functions $g_i \in V_0$.

Definition 3.8. Let A be a partial assignment. A path of length 2 from $f \in V_2$ to $g \in V_0$ is *good* if $A(f) = A(g)$. Otherwise it is *bad*.

Observe that for a function $f \in V_2$ of type $(2,2)$, no matter how we assign the value of f, it will always contribute 2 good paths and 2 bad paths.

Definition 3.9. Let A be a partial assignment that assigns value to all variables in V_0 and all $(4,0)$ and $(3,1)$ variables in V_2.

Let B_0 be the number of bad paths starting from the $(4,0)$ and $(3,1)$ variables, and let B_1 be the number of $(2,2)$ variables. Let $B := B_0 + 2B_1$. We say that B is *the number of bad paths of assignment A*.

Definition 3.10. Consider a function $f \in V_1$ and a partial assignment A to variables in $V_0 \cup V_2$. We say that f is of type (a,b,c) if in the partial assignment, there are a good paths, b bad paths and c undetermined-paths going through f. Note that $a+b+c = 7$.

A function is *switched* if it has no good path through it, and is *fully switched* if it is of type $(0,7,0)$.

Given a partial assignment as in Definition 3.9, if we assign values to variables in V_1 according to their closest variable in V_0, then we get an assignment that violates exactly a weight of B of edges. Switching the assignment of f only benefits if f is of type $(0,b,c)$, in which case switching the value of f decreases uval by at most 2. Therefore, given a partial assignment A whose number of bad paths is B with C switched functions, the best way to extend it to a full assignment violates at least $B - 2C$ edges.

The proof focuses on the partial assignment to variables in V_2, since this decides both the number of bad paths and the number of switched functions. One natural assignment is the majority assignment, where one sets $A(f)$ for $f \in V_2$ according to the majority assignment of the four associated affine functions of f (and breaks tie arbitrarily). The overall proof idea is to show that no assignment does better than this majority assignment. In particular, we prove that no matter how we change the assignment of some of the $(4,0)$ and $(3,1)$ variables to anti-majority and increase the number of bad paths B by some number Q, we will never be able to increase the number of functions with no good paths through them by more than $Q/2$. Thus, the weight of violated constraints will never decrease under non-majority assignments.

This completes the proof. $\square$

3.1 Assignments at distance 1 from Had_3

In this section, we prove Lemma 3.5.

Proof of Lemma 3.5: Let A be a partial assignment that assigns values to variables in V_0, such that there exists $x_0 \in \{-1,1\}^3$, and $l_0 \in V_0$, such that $A(f) = f(x_0)$ for all $f \in V_0 \setminus \{l_0, -l_0\}$, and $A(b \cdot l_0) = -b \cdot l_0(x_0)$ for $b \in \{-1,1\}$. We call $\pm l_0$ the corrupted affine functions.

Of the 112 functions in V_2, 56 are associated with $\pm l_0$, and 56 are not. The 56 functions that are not associated with $\pm l_0$ are all $(3,1)$ functions by item (7) of Proposition 2.32.

Let $f \in V_2$ be a function that is associated with $a_0 \in \{l_0, -l_0\}$. If f is such that $a_0(x_0) \neq f(x_0)$, then it is a $(4,0)$ function. There are $56/(2 \cdot 2) = 14$ such functions. Otherwise, it is a $(2,2)$ function. The following observation summarizes the above discussion on the types of functions in V_2.

Proposition 3.11. *Of the* 112 *functions in* V_2*,* 56 *are not associated with* $\pm l_0$ *and all of these 56 have type* $(3,1)$*. Of those that are associated with* $\pm l_0$*,* 14 *have type* $(4,0)$*, and the remaining* 42 *have type* $(2,2)$.

As discussed above, given a partial assignment to V_0, we need to decide, for the $(4,0)$ and $(3,1)$ functions in V_2, whether we assign them the majority assignment. The analysis in this section proceed in two steps. We first argue that for any assignment for the $(3,1)$ variables, to minimize the weight of violated constraints, either all $(4,0)$ variables are assigned according to majority of their associated functions in V_0, or all of them are assigned according to anti-majority. It is then easy to argue that the cost will be high in the case where all $(4,0)$ variables are assigned according to anti-majority. Then, assuming that the $(4,0)$ variables are assigned according to majority, we prove that the $(3,1)$ variables should also be assigned according to majority. This gives us a sufficient lower-bound for the weight of violated constraints.

Let us first classify the variables in V_1 with respect to the majority assignment for V_2 and see how different classes of variables relate to each other. We first consider those that are neighbors of the corrupted affine functions.

Proposition 3.12. *Let A be a partial assignment where variables in V_2 are assigned according to majority. The following properties hold:*

1. *Each corrupted function has* 1 *neighbor in* V_1 *of type* $(7,0,0)$ *and* 7 *neighbors of type* $(1,0,6)$*. This contributes a total of* 2 *functions of type* $(7,0,0)$ *and* 14 *functions of type* $(1,0,6)$.
2. *The* $(7,0,0)$ *functions obtained by starting from* $\pm l_0$ *and flipping the value at* x_0*. All 7 neighbors in* V_2 *of the* $(7,0,0)$ *functions have type* $(4,0)$*. Note that this gives a total of* 14 *functions of type* $(4,0)$*, and those are exactly all the* $(4,0)$ *functions.*

Proof. The proof is illustrated in Figure 2.

Consider a path starting from $a_0 \in \{\pm l_0\}$. Let f_1 be the function obtained by flipping the value of a_0 at x_0. We then flip some other value y_0 to get to some function $f \in V_2$. Since $f(x_0) \neq a_0(x_0)$, by (7) of Proposition 2.32, we know that a_0 is the unique function associated with f that disagrees with f on x_0. Since $A(f) = -a_0(x_0)$, we have that f is a $(4,0)$ variable. There are $2 \times 7 = 14$ such paths, and each

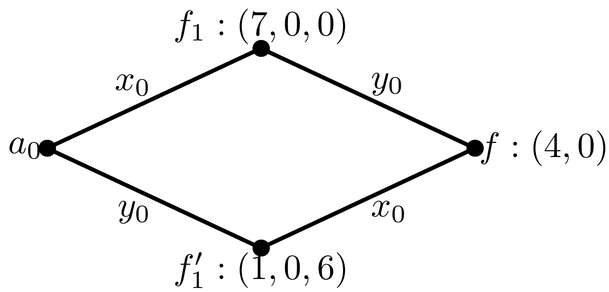

Figure 2: The $(7,0,0)$ and $(1,0,6)$ neighbors of a $(4,0)$ function.

of them end at a distinct $(4,0)$ variable. This argument also shows that all 7 V_2-neighbors of f_1 are of $(4,0)$-type and hence such f_1 is a $(7,0,0)$ variable.

Suppose now that we start at a_0 and flip the value at y_0 to get function f'_1. If we further flip x_0, we again arrive at f. On the other hand, if we flip some value other than x_0 or y_0, we get a function in V_2 of type $(2,2)$. This means that f'_1 is a $(1,0,6)$ function. □

We can now describe all neighbors of the $(4,0)$ functions.

Proposition 3.13. *Let A be a partial assignment where variables in V_2 are assigned according to majority. Then there are* 14 *functions in V_2 of type* $(4,0)$. *Each of them has 1 neighbor of type* $(7,0,0)$*, 1 of type* $(1,0,6)$*, and 6 of type* $(6,0,1)$.

Moreover, each $(6,0,1)$ *function that is adjacent to a* $(4,0)$ *function actually has 2 neighbors of type* $(4,0)$*, 1 of type* $(2,2)$ *and 4 of type* $(3,1)$. *There are* $14 \times 6/2 = 42$ *such* $(6,0,1)$ *functions.*

Proof. From Proposition 3.12, we can obtain all $(4,0)$ functions by starting at some corrupted affine function a_0, flip x_0 together with some other bit y_0. Let f be such a function.

We already have from the above that on the 2 paths from f to a_0, we have 1 function of type $(7,0,0)$ and one of type $(1,0,6)$.

To understand the other neighbors of f, consider the three affine functions g_1, g_2 and g_3 associated with f that are not a_0. We have that for any $g \in \{g_1, g_2, g_3\}$, $g(x_0) \neq a_0(x_0)$ and $g(y_0) \neq a_0(y_0)$. To each of those affine functions there are 2 paths from f, giving a total of 6 paths. We now show that all six V_1 variables on these 6 paths have type $(6,0,1)$.

Let $f_2 \in V_1$ be one of the functions on these 6 paths, and let a_1 be its associated affine function. We know that $a_1(x_0) = f_2(x_0) \neq a_0(x_0)$, $d_H(f_2, a_0) = 3$. Now consider the affect of flipping different values in f_2.

- In order to get to the $(7,0,0)$ neighbor of f from f_2, we need to flip two bits. We can flip them in two different orders, so this gives us two different paths of length 2, each going through a different $(4,0)$ function (because $(7,0,0)$ functions only have $(4,0)$ neighbors).

- If we flip value x_0 of function f_2 and get function f', then we have that $d_H(f', a_0) = 2$ and thus f' is associated with a_0. We also have that $d_H(f', a_1) = 2$, so f' is also associated with a_1. Note that $a_1(x_0) \neq f'(x_0) = a_0(x_0)$, which means that $A(a_1) = A(a_0) \neq f'(x_0)$, and thus f' is a $(2,2)$ function.

- For all the other V_2-neighbors of f_2, we have that they agree with f_2 on x_0. Also, note that the above two cases cover all 3 paths from f_2 to a_0. Thus for the remaining V_2-neighbors of f_2, we have that they all have distance 4 from a_0. This means that those functions are not associated with $\pm l_0$, and therefore are $(3,1)$ functions contributing a good path to f_2.

This concludes the analysis. □

We now consider the neighbors of the uncorrupted affine functions. Note that we have already characterized some of them in the above Proposition 3.13.

Proposition 3.14. *Let A be a partial assignment where variables in V_2 are assigned according to majority. Then each uncorrupted affine function has 4 neighbors of type $(3,1,3)$, 1 of type $(0,4,3)$, and 3 of type $(6,0,1)$. Functions of type $(3,1,3)$ and $(0,4,3)$ do not have neighbors of type $(4,0)$.*

Proof. Let a_1 be an arbitrary affine function that is not corrupted, and a_0 now be the corrupted affine function such that $a_0(x_0) = a_1(x_0)$. Choose one of the four bits where a_0 and a_1 differ, let us assume that we have chosen y_0.

Starting from a_1, let g_1 be the function where we flip the value $a_1(y_0)$. If we flip any of the three remaining bits where g_1 and a_0 differ, we get a function that is at distance 2 from a_0, and agrees with both a_0 and a_1 on x_0. This is a $(2,2)$ function. Otherwise, we get a $(3,1)$ function.

There are two subcases for the latter case, in which we flip one bit that a_0 and a_1 agree on: if we flip x_0 and get function g_2, then taking the majority assignment for g_2 gives us a bad path at g_1; otherwise we get a good path.

We thus conclude that in this case g_1 is a $(3,1,3)$ function, and all good and bad paths through it are from $(3,1)$ functions. There are $14 \times 4 = 56$ such functions g_1.

Now let g' be the function obtained by starting at a_1 and flipping the value at x_0. If we then flip any of the three remaining bits where a_0 and a_1 agree, we get a function in V_2 that is associated with $-a_0$ and is of type $(2,2)$. Otherwise, if we flip one of the 4 bits on which a_0 and a_1 disagree, we get a $(3,1)$ function that contributes a bad path. This gives us 14 functions in V_1 of type $(0,4,3)$.

If we start at a_1 and flip one of the 3 remaining bits, we get a $(6,0,1)$ function.

This completes the proof. □

We have now described the types of all 128 functions in V_1: 2 of type $(7,0,0)$, 14 of type $(1,0,6)$, 42 of type $(6,0,1)$, 56 of type $(3,1,3)$, and 14 of type $(0,4,3)$. Given a partial assignment to the affine variables as well as the $(4,0)$ and $(3,1)$ variables in V_2 (where they are assigned according to the majority of the assignments to their associated affine functions), and a function $f \in V_1$, let a_0 be the closest corrupted affine function, and let a_1 be the closest affine function. We can decide the type of f by checking whether $d_H(f,a_0)$ is 1 or 3, whether $f(x_0) = a_0(x_0)$, and if $d_H(f,a_0) = 3$, whether $f(x_0) = a_1(x_0)$. The details are in the above arguments and we summarize the result below.

Proposition 3.15. *Fix a partial assignment as above. Let $f \in V_1$, a_0 be its closest corrupted affine function, and a_1 be its closest affine function. We have the following regarding the type of f:*

- *If $a_0 = a_1$ and thus $d_H(f,a_0) = 1$, then f has type $(7,0,0)$ if and only if $f(x_0) = a_0(x_0)$, and otherwise it has type $(1,0,6)$.*

- *If $a_0 \neq a_1$, but $a_0(x_0) = a_1(x_0) = f(x_0)$, then f is a $(3,1,3)$ function.*
- *If $a_0 \neq a_1$, $f(x_0) \neq a_1(x_0)$, $a_0(x_0) \neq a_1(x_0)$, then f is a $(0,4,3)$ function.*
- *If $a_0 \neq a_1$, $f(x_0) = a_1(x_0)$, $a_0(x_0) \neq a_1(x_0)$, then f is a $(6,0,1)$ function.*

Finally, we describe the neighbors of the $(3,1)$ functions in V_2.

Proposition 3.16. *Let A be a partial assignment where variables in V_2 are assigned according to majority. Each $(3,1)$ function contributes 1 good path each to 3 $(3,1,3)$ functions, 1 good path each to 3 $(6,0,1)$ functions, and 1 bad path to 1 $(0,4,3)$ function and 1 bad path to 1 $(3,1,3)$ function.*

Proof. Let f now be a $(3,1)$ function. There are 6 good paths coming from it and going into 3 uncorrupted V_0 variables, and 2 bad paths going to another uncorrupted variable in V_0.

Consider a pair of good paths that go to the same affine function a_1. We now argue that exactly one of the two V_1-variables is $(3,1,3)$, and the other is $(6,0,1)$.

Let a_0 be the corrupted affine function such that $a_1(x_0) = a_0(x_0)$. Since f is a $(3,1)$ function, it is not associated with any corrupted affine functions. Therefore, on the paths from a_1 to f, we flip exactly one bit x such that $x \neq x_0$ and $a_1(x) = a_0(x)$, and another bit y such that $a_1(y) \neq a_0(y)$. By Proposition 3.15, we have that starting from a_1, if we first flip y, we get a $(3,1,3)$ function. If we first flip x, then the closest corrupted affine function becomes $-a_0$ rather than a_0, and in this case we get a $(6,0,1)$.

Now we turn to the pair of bad paths, and let a_2 be the affine function at the end of the bad paths. Note that $d_H(f,a_2) = 2$, one of the bits on which they differ is x_0, and we denote the other by y. Since f is a $(3,1)$ function, we have that $d_H(f,a_0) = 4$, therefore it must be that $a_0(y) \neq a_2(y)$. Therefore, starting from a_2, if we first flip x_0 and get function $f' \in V_1$, then the closest corrupted affine function to f' becomes $-a_0$, and $f'(x_0) = -a_2(x_0) = -a_0(x_0)$, thus by Proposition 3.15, the function f' is a $(0,4,3)$ function.

Otherwise, if we first flip y, then for the resulting function f', the closest corrupted affine function is a_0, $f'(x_0) = a_2(x_0) = a_0(x_0)$, and therefore f' is a $(3,1,3)$ function. □

The following proposition show that in an optimal assignment, all $(4,0)$ variables should be assigned according to majority, unless all of them are flipped.

Proposition 3.17. *Let A be a partial assignment to variables in V_0 as defined at the beginning of this subsection. For any partial assignment to the $(3,1)$ and $(2,2)$ variables, we can assume that the assignment to the $(4,0)$ variables that minimizes the weight of violated constraints either assigns the $(4,0)$ variables according to majority, or assigns the $(4,0)$ variables according to the negation of majority.*

Proof. Fix an assignment to all variables of type $(3,1)$ and $(2,2)$.

We start by analyzing the majority assignment to the $(4,0)$ variables. Under this assignment, the $(7,0,0)$ functions only have $(4,0)$ neighbors and thus have 7 good paths through them. The $(6,0,1)$ functions have 2 neighbors of type $(4,0)$ and thus have at least 2 good paths through each of them, and the $(1,0,6)$ functions have at least 1 good path going through each of them.

Every time we change the assignment of one of those $(4,0)$ variables, we will introduce 8 bad paths (actually we flip those assignments in pairs—the variable and its negation—and we will get 16 in each step). The key is to bound the number of variables in V_1 that are now switched. Suppose we flipped

$0 < k < 14$ of the $(4,0)$ functions, in the best case we have made k of the $(1,0,6)$ functions switched, and $6k/2 = 3k$ of the $(6,0,1)$ functions switched. Note that unless we flip all $(4,0)$ functions, we will never make the $(7,0,0)$ functions switch. Therefore as long as $0 < k < 14$, we will increase the number of bad paths by $8k$ but will only get at most $4k$ more switched functions. This means that unless we flip all assignments of $(4,0)$ functions to anti-majority, the value of the assignment will never be better than having all $(4,0)$ functions be assigned to majority. □

Next we show that suppose the $(4,0)$ functions are all fixed to majority, then the best assignment assigns majority to the $(3,1)$ functions.

Proposition 3.18. *Let A be a partial assignment to variables in V_0 as defined at the beginning of this subsection. If all $(4,0)$ variables in V_2 are assigned according to majority, then to complete this assignment and minimize the weight of violated constraints, one should set all $(3,1)$ variables according to majority.*

Proof. We start by assigning all $(3,1)$ variables according to the majority assignments of their associated affine variables, and compare the number of bad paths introduced by each flip against the potential number of switched function we get. Note that of all the types of V_1 functions we have, after setting the $(4,0)$ variables to majority, the only potential functions that might not have good paths through them have type $(3,1,3)$ or $(0,4,3)$. Note that for $(0,4,3)$ functions, all bad paths come from $(3,1)$ functions, thus flipping some $(3,1)$ to non-majority only contributes good paths to some $(0,4,3)$ functions and thus potentially decrease the number of fully switched functions. In order to upper-bound the maximum number of fully switched function, we can safely ignore the effect of those functions and only focus on the $(3,1,3)$ functions.

Now suppose that we change k of the $(3,1)$ functions to anti-majority assignment. Then we get $4k$ extra bad paths, and the number of switched functions will increase by at most $3k/3 = k < 4k/2$ (every flip impacts 3 $(3,1,3)$ functions, and each $(3,1,3)$ function needs 3 flips such that the number of good paths becomes 0.) This means that in this case anything other than the majority assignment to the $(3,1)$ functions gives a worse assignment. □

Finally, we show that flipping all $(4,0)$ functions to anti-majority is not a good idea. In this case, the number of bad paths after assigning anti-majority to $(4,0)$ and before assigning the $(3,1)$ and $(2,2)$ functions is $14 \cdot 8 = 112$. With respect to the assignment where $(4,0)$ functions are assigned anti-majority and $(3,1)$ functions are assigned majority, we have 2 functions in V_1 of type $(0,7,0)$, 42 functions of type $(4,2,1)$, 14 functions of type $(0,1,6)$, 56 of type $(3,1,3)$ and 14 of type $(0,4,3)$.

We now show that all $(3,1)$ functions should be assigned according to majority. Essentially, every flip of a $(3,1)$ function decreases the number of good paths in 3 $(3,1,3)$ functions and 3 $(4,2,1)$ functions. After flipping k of the $(3,1)$ variables away from majority, the increase in the number of switched function is at most $3k/3 + 3k/4 = 7k/4 < 4k/2$, not enough to make up the increased number of bad paths. If we assign majority to the $(3,1)$ functions, then we already have 224 bad paths and 336 undetermined paths, thus the total number of bad paths regardless of the assignment to the $(2,2)$ functions will be $224 + 336/2 = 392$, and the number of switched function is at most 16, giving a minimum cost of $392 - 2 \cdot 16 = 360$.

On the other hand, if we take the all majority assignment, we get 280 bad paths and at most 14 switched function, giving a minimum cost of $280-2\cdot 14=252$.

This completes the proof of the lemma. □

3.2 Assignments at distance 2 from Had_3

In this section, we prove Lemma 3.6

Proof. Let A be a partial assignments to variables in V_0 such that the assignment is distance 2 from satisfying the Had_3 predicate. That is, there exists $x_0 \in \{-1,1\}^3$, and $l_0, l_1 \in V_0$, $l_0 \neq \pm l_1$, such that $A(f) = f(x_0)$ for all $f \in V_0 \setminus \{\pm l_0, \pm l_1\}$, and $A(f) = -f(x_0)$ otherwise. Note that there are multiple choices of x_0 and the identity of l_0 and l_1 depends on the choice of x_0. Here we pick x_0 arbitrarily from all the possible options. We call $\pm l_0$ and $\pm l_1$ corrupted affine functions. Our goal is to show that the total weight violated by A is at least 288.

The functions in V_2 are of three types: the ones that contain neither of l_0 and l_1 as associated linear functions, the ones that contain one of them and the ones that contain both. Functions of the first and the third type are all $(3,1)$ functions, and functions of the second type can be either $(4,0)$ or $(2,2)$.

We first describe the types of variables in V_2.

Proposition 3.19. *Given a partial assignment to variables in V_0 that is at distance 2 from an assignment that satisfies Had_3, the following properties hold:*

1. *There are 24 functions associated with 2 corrupted affine functions. All of them have type $(3,1)$.*
2. *There are 24 functions associated with 0 corrupted affine functions. All of them have type $(3,1)$.*
3. *Of the functions associated with 1 corrupted affine function, 16 have type $(4,0)$, and 48 have type $(2,2)$.*

Proof. Let a_0 be some arbitrary corrupted affine function, and let a_1 be the other corrupted affine function with $a_0(x_0) = a_1(x_0)$.

Let f be a function in V_2 obtained from a_0 by flipping x_0 together with one of the bits y_0 where a_0 and a_1 disagrees. Therefore we have $d_H(f, a_1) = 4$, so f is only associated with 1 corrupted affine function. Also, note that the assignments to the associated affine functions of f all agree, so f is a $(4,0)$ function. This gives $4\times 4 = 16$ functions of type $(4,0)$.

Consider now some function $f \in V_2$ obtained from a_0 by flipping x_0 as well as one of the other bits where a_0 and a_1 agrees. This means that $d_H(f, -a_1) = 2$, so f is associated with 2 corrupted affine functions and has type $(3,1)$. There are $2\times 2 = 4$ ways to pick the corrupted affine functions that f is associated with, and each pair gives $\binom{4}{2} = 6$ different functions in V_2. Therefore we get 24 functions of this type.

Next, consider starting from a_0, flip 1 bit on which a_0 and a_1 agrees other than x_0, and 1 bit on which a_0 and a_1 disagree. The resulting function f is again only associated with 1 corrupted affine function, and has type $(2,2)$. There are 48 functions of this type.

Finally, we count the functions that are not associated with any corrupted functions. Let a_2 be an uncorrupted affine function, and we assume that a_0 and a_1 both agree with a_2 on x_0. Note also that a_0, a_1 and a_2 are all at distance 4 from each other. We have that the size of the following sets are all 2:

$$\left\{x \in \{-1,1\}^3 \mid a_0(x) = a_1(x) = a_2(x)\right\}, \tag{3.1}$$

$$\left\{x \in \{-1,1\}^3 \mid a_0(x) = a_1(x) = -a_2(x)\right\}, \tag{3.2}$$

$$\left\{x \in \{-1,1\}^3 \mid a_0(x) = -a_1(x) = -a_2(x)\right\}, \tag{3.3}$$

$$\left\{x \in \{-1,1\}^3 \mid a_0(x) = -a_1(x) = a_2(x)\right\}. \tag{3.4}$$

Starting from a_2, in order to reach some $f \in V_2$ that is not associated with any corrupted affine functions, we can either choose one bit to flip from (3.1) and one from (3.2), or choose one bit from (3.3) and another from (3.4). Thus from each a_2, we can reach 8 different functions in $f \in V_2$ that are not associated with any uncorrupted affine function. Each of these f is in turn associated with 4 functions in V_0 like a_2. Therefore, the total number of functions $f \in V_2$ that are not associated with any corrupted affine functions is $12 \times 8/4 = 24$. □

Now we turn to the neighbors of the affine functions.

Proposition 3.20. *Given a partial assignment to variables in V_0 that is at distance 2 from an assignment that satisfies Had_3, the following properties hold:*

- *All affine functions have 1 $(7,0,0)$ neighbor, 3 $(1,2,4)$ neighbors and 4 $(4,0,3)$ neighbors. This gives a total of 16 $(7,0,0)$ functions, 48 $(1,2,4)$ functions and 64 $(4,0,3)$ functions.*
- *All $(7,0,0)$ functions have 4 $(4,0)$ neighbors and 3 $(3,1)$ neighbors.*
- *All $(1,2,4)$ functions get 1 good path from a $(3,1)$ function, 2 bad paths from 2 $(3,1)$ functions, and 4 undetermined paths from 4 $(2,2)$ functions.*
- *All $(4,0,3)$ functions get 1 good path from a $(4,0)$ function, 3 good paths from 3 $(3,1)$ functions, and 3 undetermined paths from 3 $(2,2)$ functions.*

Proof. As in the previous proof, let a_0 be some arbitrary corrupted affine function, and let a_1 be the other corrupted affine function with $a_0(x_0) = a_1(x_0)$.

Let $g \in V_1$ be the function obtained by flipping x_0 from a_0. As in the argument of Proposition 3.19, if we further flip one bit on which a_0 and a_1 disagree, we get a $(4,0)$ function. If we flip one bit on which a_0 and a_1 agrees, then we get a function that contributes a good path to g and is associated with a_0 and $-a_1$, and thus is of type $(3,1)$. Thus g is of type $(7,0,0)$, and it has 4 $(4,0)$ neighbors and 3 $(3,1)$ neighbors.

Now let g be the function obtained by flipping in a_0 some bits other than x_0 where a_0 and a_1 agrees. As in the argument of Proposition 3.19, if we further flip x_0, then we get a $(3,1)$ function contributing a good path to g. If instead we flip the remaining 2 bits where a_0 and a_1 agree, we get another $(3,1)$ function contributing a bad path to g. Finally, if we flip one of the 4 bits where a_0 and a_1 disagree, by the argument in Proposition 3.19, we get a $(2,2)$ function. Therefore in this case g is of type $(1,2,4)$, with 1 $(3,1)$ neighbor contributing a good path, 2 $(3,1)$ neighbors each contributing a bad path, and 4 $(2,2)$ neighbors.

Next, let g be the function obtained by flipping in a_0 some bits where a_0 and a_1 disagrees. By the proof of Proposition 3.19, if we now flip x_0, we get a $(4,0)$ function; also if we flip another bit where a_0 and a_1 agree, we get a $(2,2)$ function. If we instead flip one bit where a_0 and a_1 disagree, we get a function contributing a good path to g (note that in this case the majority assignment to f actually assigns $-f(x_0)$) and is associated with a_0 and a_1, which means that f is of type $(3,1)$. Thus, g is a $(4,0,3)$ function with 1 $(4,0)$ neighbor, 3 $(3,1)$ neighbors and 3 $(2,2)$ neighbors.

Now we turn to neighbors of uncorrupted affine functions. Let a_2 be an uncorrupted affine function, and let a_0, a_1 be the two corrupted affine functions with $a_0(x_0) = a_1(x_0) = a_2(x_0)$.

First, consider the function g obtained from a_2 by flipping x_0. If we flip the other bit where a_0, a_1 and a_2 all agree, we get a function in V_2 that is associated with $-a_0$ and $-a_1$. This function has type $(3,1)$ and contributes a good path to g. If instead we flip the two bits in (3.2), we get a function that is not associated with any corrupted affine functions, and it contributes a bad path to g. If we flip the remaining four bits, we get a function that is associated with only 1 corrupted affine function, and it has type $(2,2)$. We conclude that g is a $(1,2,4)$ function and the profile of its neighbors is the same as above.

Next, consider flipping the bit other than x_0 where a_0, a_1 and a_2 all agree, and let g be the resulting function. As discussed above, if we now flip x_0, we get a $(3,1)$ function with a good path. On the other hand, if we now flip one of the 2 bits in (3.3), we get a function that is associated with only 1 corrupted affine function, namely $-a_1$. This is a $(4,0)$ function. The situation is the same if we flip one of the 2 bits in (3.4). If we flip one of the 2 bits in (3.2) instead, we get a function associated with no corrupted affine function, and it contributes a good path to g. We conclude that in this case g is $(7,0,0)$ and the profile of its neighbors is the same as above.

Now, let g be the one obtained by flipping one of the bits in (3.2). If we now flip x_0, we get a $(3,1)$ function with a bad path, as discussed above. If we flip the other bit in (3.1), we get a $(3,1)$ function with a good path, as discussed above. If we flip another bit in (3.2), we get a $(3,1)$ function associated with a_0 and a_1 that contributes a bad path. If we flip one of the bits in (3.3) or (3.4), we get a $(2,2)$ function. Therefore, again g is a $(1,2,4)$ function with the same profile as above.

The remaining cases are where we obtain g by flipping one of the bits in (3.3) or (3.4) first. These cases are symmetric, so without loss of generality, suppose the bit flipped is in (3.3). By the discussion above, if we now flip one of the bits in (3.1) or (3.2), we get 1 $(4,0)$ function and 3 $(2,2)$ functions. If we flip another bit in (3.3), we get a function associated with 2 corrupted affine functions with a good path. If we flip one of the bits in (3.4), we get a function not associated with any corrupted affine function that also contributes a good path. We conclude that g is of type $(4,0,3)$ with the same profile as above. □

We can use similar arguments to characterize the neighbors of functions in V_2.

Proposition 3.21. *Given a partial assignment to variables in V_0 that is at distance 2 from an assignment that satisfies* Had_3*, the following properties hold:*

- *All $(4,0)$ functions have 4 neighbors of type $(7,0,0)$ and 4 of type $(4,0,3)$.*
- *All $(3,1)$ functions have 1 neighbors of type $(7,0,0)$, 4 of type $(4,0,3)$, 2 of type $(1,2,4)$ getting bad paths and 1 of type $(1,2,4)$ getting a good path.*

We can now conclude the proof of this section by arguing that assignments that assign according to majority for the $(4,0)$ and $(3,1)$ functions never do worse than other assignments.

Suppose we flip k of the $(4,0)$ functions and k of their negations away from majority. At most $8k$ functions of type $(4,0,3)$ will switch, and $(7,0,0)$ functions will not switch unless $4 \le k \le 8$. This means that for a fixed assignment to the $(3,1)$ and $(2,2)$ functions, the weight of violated constraints will not be less than that of assigning majority to all $(4,0)$ functions, unless $k \ge 4$.

Further, observe that if two $(7,0,0)$ functions f and g share a $(4,0)$ neighbor, then $d_H(f,g) = 2$. Therefore they share exactly $2! = 2$ $(4,0)$ neighbors. Thus if $k = 4,5$, at most 1 $(7,0,0)$ function and its negation will be switched.

Let us consider the case when $k = 4$. We are flipping 8 $(4,0)$ functions, generating 64 bad paths. This should be compensated by turning at least 32 functions from the set of $(7,0,0)$ and $(4,0,3)$ functions into functions that have no good paths. Suppose we choose $0 \le k_1 \le 1$ of the $(7,0,0)$ functions and $0 \le k_2 \le 64$ of the $(4,0,3)$ functions, where $k_1 + k_2 = 32$. Each $(7,0,0)$ is connected to a set of 3 $(3,1)$ functions, and these sets are disjoint for different $(7,0,0)$ functions. Therefore, at least $3k_1$ of the $(3,1)$ functions need to be flipped. Also, each $(4,0,3)$ is connected to a set of 3 $(3,1)$ functions, and each $(3,1)$ function is connected to 4 $(4,0,3)$ functions, therefore at least $3k_2/4$ $(3,1)$ functions need to be flipped. Moreover, the number of functions flipped must be even because we are flipping both the function and its negation. Combining this, we conclude that at least 24 of the $(3,1)$ needs to be flipped, contributing 96 new bad paths. This means that we now have $64 + 96 = 160$ bad paths and would like to find at least 80 functions in V_1 that will potentially switch. This is the total number of $(7,0,0)$ and $(4,0,3)$ functions, and since we assumed that we only switch 1 of the $(7,0,0)$ functions, which means that it is already impossible.

For $k > 4$, the number of functions we need to potentially switch will only be higher, and therefore flipping $(4,0)$ is never optimal.

Once we have that the $(4,0)$ functions should be assigned majority, the rest of the argument is easy. The only function that could possibly switch are the $(1,2,4)$ functions. However, when we flip a $(3,1)$, we get 4 bad paths and could expect to gain at most 1 switched function. Therefore flipping $(3,1)$ in this case will always increase the weight of violated constraints.

It is then easy to see that under the majority assignment, there is no switched function, and the total number of bad paths is 288. $\square$

4 Optimality of the $11/8$-gadget

In this section, we will construct an optimal solution to the dual LP given in Definition 2.30. This yields the following theorem.

Theorem 4.1. *[Theorem 1.8 restated] The value of the LP in Definition 2.30 is* $11/64$. *As a result, for every* (c,s)*-gadget reducing Max-*Had_3 *to Max-*2-Lin(2),

$$\frac{s}{c} \le \frac{11}{8}.$$

In other words, the gadget given in Theorem 3.1 is optimal *among gadget reductions from Chan's* 7*-ary Hadamard predicate.*

Proof. Our goal is to construct $\mathcal{A} \in \mathsf{R}(\mathsf{Had}_3)$, i. e., a folded distribution of assignments which is random on the primary variables. For $i \in \{0,1,2\}$, denote by $\mathsf{R}_i(\mathsf{Had}_3)$, the set of distributions $\mathcal{A}_i$ such that the string

$$\left(A\left(\chi_\emptyset\right), A\left(\chi_{\{1\}}\right), A\left(\chi_{\{2\}}\right), A\left(\chi_{\{3\}}\right), A\left(\chi_{\{1,2\}}\right), A\left(\chi_{\{1,3\}}\right), A\left(\chi_{\{2,3\}}\right), A\left(\chi_{\{1,2,3\}}\right)\right)$$

is, over a random $A \sim \mathcal{A}_i$, distributed like a uniformly random element of $\{-1,1\}^8$ which is distance i from satisfying the Had_3 predicate. To prove Theorem 4.1, we will construct three separate distributions $\mathcal{A}_0$, $\mathcal{A}_1$, and $\mathcal{A}_2$ with the property that $\mathcal{A}_i \in \mathsf{R}_i(\mathsf{Had}_3)$ for each $i \in \{0,1,2\}$. Then, using Proposition 2.33, we will set

$$\mathcal{A} = \frac{1}{16}\mathcal{A}_0 + \frac{1}{2}\mathcal{A}_1 + \frac{7}{16}\mathcal{A}_2\,.$$

Using (1) of Proposition 2.32, we can decompose $\{-1,1\}^8 = V_0 \cup V_1 \cup V_2$. A length-one edge (x,y) in $\{-1,1\}^8$ has one of two types: either it goes between V_0 and V_1, or it goes between V_1 and V_2. Each $\mathcal{A}_i$ distribution we construct will perform equally well on edges of a given type. As a result, for each distribution $\mathcal{A}_i$, we only need to keep track of two numbers, one for each edge type. To do so, for any fixed edge (x,y) of type $V_0 \leftrightarrow V_1$, define

$$\mathsf{val}(\mathcal{A}', V_0 \leftrightarrow V_1) := \Pr_{A \sim \mathcal{A}'}[A(x) = A(y)]\,,$$

and define $\mathsf{val}(\mathcal{A}', V_1 \leftrightarrow V_2)$ analogously. For convenience in this section, we will keep track of these $\mathsf{val}(\cdot)$ parameters rather than the corresponding $\mathsf{uval}(\cdot)$ parameters.

For each $i \in \{0,1,2\}$, our goal is to construct the $\mathcal{A}_i$ which strikes the right balance between making $\mathsf{val}(\mathcal{A}_i, V_0 \leftrightarrow V_1)$ large and making $\mathsf{val}(\mathcal{A}_i, V_1 \leftrightarrow V_2)$ large. The next three lemmas show what we achieve.

Lemma 4.2. *There exists a distribution $\mathcal{A}_0 \in \mathsf{R}_0(\mathsf{Had}_3)$ such that*

$$\mathsf{val}(\mathcal{A}_0, V_0 \leftrightarrow V_1) = \frac{7}{8} \quad \textit{and} \quad \mathsf{val}(\mathcal{A}_0, V_1 \leftrightarrow V_2) = \frac{7}{8}\,.$$

Lemma 4.3. *There exists a distribution $\mathcal{A}_1 \in \mathsf{R}_1(\mathsf{Had}_3)$ such that*

$$\mathsf{val}(\mathcal{A}_1, V_0 \leftrightarrow V_1) = \frac{25}{32} \quad \textit{and} \quad \mathsf{val}(\mathcal{A}_1, V_1 \leftrightarrow V_2) = \frac{7}{8}\,.$$

Lemma 4.4. *There exists a distribution $\mathcal{A}_2 \in \mathsf{R}_2(\mathsf{Had}_3)$ such that*

$$\mathsf{val}(\mathcal{A}_2, V_0 \leftrightarrow V_1) = \frac{7}{8} \quad \textit{and} \quad \mathsf{val}(\mathcal{A}_2, V_1 \leftrightarrow V_2) = \frac{43}{56}\,.$$

By setting $\mathcal{A} := \frac{1}{16}\mathcal{A}_0 + \frac{1}{2}\mathcal{A}_1 + \frac{7}{16}\mathcal{A}_2$, we see that

$$\mathsf{val}(\mathcal{A}, V_0 \leftrightarrow V_1) = \mathsf{val}(\mathcal{A}, V_1 \leftrightarrow V_2) = \frac{53}{64}\,.$$

Finally, $1 - 53/64 = 11/64$, and this is the number guaranteed by the theorem.

We now prove Lemmas 4.2, 4.3, and 4.4. The first two are straightforward, but Lemma 4.4 is relatively involved.

Proof of Lemma 4.2. The distribution $\mathcal{A}_0$ simply picks a random (negated) dictator assignment. More formally, it does the following:

1. Pick $b \in \{-1,1\}$ and $i \in \{1,2,\dots,8\}$ independently and both uniformly at random.
2. Let d_i be the i-th dictator function.
3. Output the function $b \cdot d_i$.

A random dictator will satisfy any fixed edge of the hypercube with probability $7/8$. Thus, it remains to prove that $\mathcal{A}_0 \in \mathsf{R}_0(\mathsf{Had}_3)$, and this is easy to check. □

Proof of Lemma 4.3. The distribution $\mathcal{A}_1$ picks a random (negated) dictator assignment and corrupts its value on a single primary variable. More formally, it does the following:

1. Sample A from $\mathcal{A}_0$.
2. Let x be a uniformly random primary variable.
3. Set $\widetilde{A}(x) := -A(x)$ and $\widetilde{A}(-x) := -A(-x)$. Set $\widetilde{A} := A$ for all other inputs.
4. Output $\widetilde{A}$.

Note that whenever $\widetilde{A}$ is generated from A, $\widetilde{A}$ and A agree on all variables in V_1 and V_2. As a result,

$$\mathsf{val}(\mathcal{A}_1, V_1 \leftrightarrow V_2) = \mathsf{val}(\mathcal{A}_0, V_1 \leftrightarrow V_2) = \frac{7}{8}.$$

Next, fix an edge (x,y) where $x \in V_0$ and $y \in V_1$. Then $\widetilde{A}$ and A agree on (x,y) unless either x or $-x$ is selected as the primary variable in Step 2, in which case they disagree on x. By (1) of Proposition 2.32, there are 16 primary variables, meaning this event occurs with probability $1/8$. As a result,

$$\mathsf{val}(\mathcal{A}_1, V_0 \leftrightarrow V_1) = \frac{7}{8} \cdot \mathsf{val}(\mathcal{A}_0, V_0 \leftrightarrow V_1) + \frac{1}{8} \cdot (1 - \mathsf{val}(\mathcal{A}_0, V_0 \leftrightarrow V_1)) = \frac{25}{32}.$$

It remains to check that $\mathcal{A}_1 \in \mathsf{R}_1(\mathsf{Had}_3)$; this follows from the fact that $\mathcal{A}_0 \in \mathsf{R}_0(\mathsf{Had}_3)$ and that $\widetilde{A}$ is chosen by randomly perturbing A on a single primary variable. □

Proof of Lemma 4.4. The distribution $\mathcal{A}_2$ is itself a mixture of two other distributions, $\mathcal{A}_2^0$ and $\mathcal{A}_2^1$. We now describe them separately and combine them later.

Constructing $\mathcal{A}_2^0$. The distribution $\mathcal{A}_2^0$ is generated by the following process:

1. Sample d_i uniformly at random from the set of dictators and negated dictators.
2. Form $\widetilde{d}_i$ by negating d_i on two uniformly random primary variables (and their negations).
3. Set $A : V \to \{-1,1\}$ to agree with $\widetilde{d}_i$ on V_0.

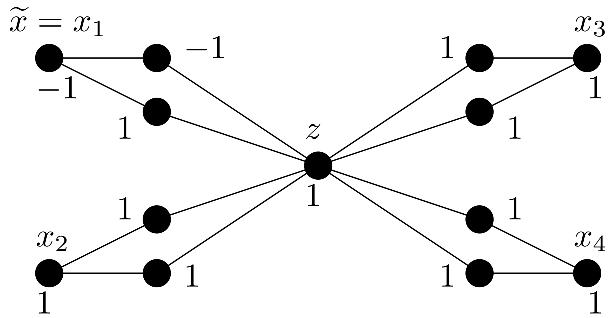

Figure 3: The neighborhood of z. The variables are labeled with the assignment d_i gives them. Note that the assignment of z agrees with all but one of its neighbors and all but one of the x_j. Further, the two variables which disagree with z are adjacent.

4. For every $y \in V_1$, let x be y's neighbor in V_0.
   - If $A(x) = d_i(x)$, set $A(y) := d_i(y)$.
   - Otherwise, set $A(y) := A(x)$.
5. For every $z \in V_2$, set $A(z)$ to the majority value of A on z's eight neighbors in V_1. (Ties will not occur.)

By the construction of A, it is immediate that $\mathcal{A}_2^0 \in \mathsf{R}_2(\{-1,1\}^8)$. As for its performance on the two edge types, we have the following proposition.

Proposition 4.5. $\mathsf{val}(\mathcal{A}_2^0, V_0 \leftrightarrow V_1) = 29/32$ *and* $\mathsf{val}(\mathcal{A}_2^0, V_1 \leftrightarrow V_2) = 167/224$.

Proof. Let $x \in V_0$ and $y \in V_1$ be neighbors. With probability $3/4$, $A(x) = d_i(x)$, in which case $A(y) = d_i(y)$. Conditioning on this event, $A(y) = A(x)$ with $7/8$ probability, as the dictator assignment satisfies each edge with probability $7/8$. On the other hand, when $A(x) \neq d_i(x)$, which happens with probability $1/4$, $A(y)$ always equals $A(x)$. Thus,

$$\mathsf{val}(\mathcal{A}_2^0, V_0 \leftrightarrow V_1) = \frac{3}{4} \cdot \frac{7}{8} + \frac{1}{4} = \frac{29}{32}.$$

To compute $\mathsf{val}(\mathcal{A}_2^0, V_1 \leftrightarrow V_2)$, we will condition the output of $\mathcal{A}_2^0$ on the choice of the (possibly negated) dictator d_i in Step 1. Let us focus on a particular $z \in V_2$. We will now describe what the immediate neighborhood of z looks like.

Let $\mathcal{N}(z) \subseteq V_1$ denote the neighborhood of z, and let x_1, x_2, x_3, and x_4 be the four points in V_0 which are distance two from z. Regardless of what d_i is, $(d_i(x_1), d_i(x_2), d_i(x_3), d_i(x_4))$ will always have a majority size of three. Furthermore, $d_i(z)$ agrees with this majority. Let $\widetilde{x} \in \{x_1, x_2, x_3, x_4\}$ be the variable in the minority, and assume without loss of generality that $\widetilde{x} = x_1$. Then of the two elements in $\mathcal{N}(z)$ which neighbor x_1, d_i assigns one a value of 1 and the other a value of (-1); for the remaining elements $y \in \mathcal{N}(z)$, $d_i(y) = d_i(z)$. A pictorial representation of this is given in Figure 3.

Consider the two primary variables which were selected in Step 2. If a given primary variable x_j is selected, then the value given to it by d_i is negated when forming A. Furthermore, all of x_j's neighbors in V_1 are assigned the value $A(x_j)$. Pictorially, if x_3 in Figure 3 was selected in Step 2, then it and its two neighbors' values would be flipped to (-1) in A. Similarly, if $\widetilde{x} = x_1$ in Figure 3 was selected, then both it and its two neighbors would be given the value 1 by A.

For a set of Boolean variables $x_1, \ldots, x_k \in \{-1, 1\}$ where there is a majority value (in other words $\sum_i x_i \neq 0$), define $\mathsf{Maj\text{-}Size}(x_1, \ldots, x_k)$ as the number of variables whose value equals the majority value. The value A assigns to z is just the majority value of z's neighbors, so A's success on the edges neighboring z will just be the fractional size of this majority. If x_1 is selected in Step 2, then the value given to every $y \in \mathcal{N}(z)$ agrees with the value given to y's neighbor in the variables x_j. Thus, in this case, the majority size of z's neighbors will just be $2 \cdot \mathsf{Maj\text{-}Size}(A(x_1), A(x_2), A(x_3), A(x_4))$. Otherwise, the two neighbors of x_1 will disagree with one another, and the majority size will be $1 + 2 \cdot \mathsf{Maj\text{-}Size}(A(x_2), A(x_3), A(x_4))$.

Now, we split into cases based on how many elements of $\{x_1, x_2, x_3, x_4\}$ were selected in Step 2. Case 0 occurs when zero were selected, Case 1 when one was selected, and so forth.

Case 0: In this case x_1 is not selected, and Maj-Size of the remaining x_j is three. As a result, the success probability is $(1 + 2 \cdot 3)/8 = 7/8$.

Case 1: We split into two subcases depending on whether x_1 was selected.

Case x_1 is selected: In this case, $\mathsf{Maj\text{-}Size}(A(x_1), A(x_2), A(x_3), A(x_4)) = 4$, and so the success probability is 1.

Case x_1 is not selected: In this case, $\mathsf{Maj\text{-}Size}(A(x_2), A(x_3), A(x_4)) = 2$, and so the success probability is $(1 + 2 \cdot 2)/8 = 5/8$.

The first subcase occurs with probability $1/4$ and the second subcase occurs with probability $3/4$. Combined, this means that A succeeds with probability $1/4 + (3/4) \cdot (5/8) = 23/32$ in this case.

Case 2: Again, we split into two subcases depending on whether x_1 was selected.

Case x_1 is selected: In this case, $\mathsf{Maj\text{-}Size}(A(x_1), A(x_2), A(x_3), A(x_4)) = 3$, so the success probability is $(2 \cdot 3)/8 = 6/8$.

Case x_1 is not selected: In this case, $\mathsf{Maj\text{-}Size}(A(x_2), A(x_3), A(x_4)) = 2$, and so the success probability is $(1 + 2 \cdot 2)/8 = 5/8$.

Both subcases occur with probability $1/2$. As a result, A succeeds in this case with probability $(1/2)(3/4 + 5/8) = 11/16$

There are $\binom{8}{2}$ possible choices for the two primary variables which were negated to form $\widetilde{d}_i$. Of these, $\binom{4}{2}$ yield Case 0, $4 \cdot 4$ yield Case 1, and $\binom{4}{2}$ yield Case 2. This gives a total success probability of

$$\mathsf{val}(\mathcal{A}_2^0, V_1 \leftrightarrow V_2) = \frac{\binom{4}{2}}{\binom{8}{2}} \cdot \frac{7}{8} + \frac{4 \cdot 4}{\binom{8}{2}} \cdot \frac{23}{32} + \frac{\binom{4}{2}}{\binom{8}{2}} \cdot \frac{11}{16} = \frac{167}{224},$$

as guaranteed by the proposition. ☐

Constructing $\mathcal{A}_2^1$. In constructing $\mathcal{A}_2^1$, it will be convenient to view V as the set of Boolean functions on 3 variables $V = \{f \mid f : \{-1,1\}^3 \to \{-1,1\}\}$. The distribution $\mathcal{A}_2^1$ is generated by the following process:

1. Pick $x_1, x_2, x_3 \in \{-1,1\}^3$.
2. Set $(x_4)_i = (x_1)_i \cdot (x_2)_i \cdot (x_3)_i$ for $i \in [3]$.
3. Pick $b_1, \dots, b_4 \in \{-1,1\}$ subject to $b_1 b_2 b_3 b_4 = -1$.
4. Set $A_1, \dots, A_4$ such that $A_i(f) = b_i \cdot f(x_i)$ for $i \in [4]$.
5. Pick a uniformly random $M : \{-1,1\}^4 \to \{-1,1\}$ subject to
   - $M(a_1, \dots, a_4) = \mathrm{sgn}(a_1 + \cdots + a_4)$ when $a_1 + \cdots + a_4 \neq 0$, and
   - $M(a_1, \dots, a_4) = -M(-a_1, \dots, -a_4)$ otherwise.
6. Output $A(f) = M(A_1(f), \dots, A_4(f))$.

The construction of $\mathcal{A}_2^1$ is similar to the construction of the variables in V_2 in the proof of (7) of Proposition 2.32. Via the correspondence shown in the proof of Proposition 2.33, item (7) of Proposition 2.32 shows that $\mathcal{A}_2^1 \in \mathsf{R}_2(\mathsf{Had}_3)$. As for its performance on the two edge types, we have the following proposition.

Proposition 4.6. $\mathsf{val}(\mathcal{A}_2^1, V_0 \leftrightarrow V_1) = \mathsf{val}(\mathcal{A}_2^1, V_1 \leftrightarrow V_2) = 13/16$.

Proof. Let $f, f' : \{-1,1\}^3 \to \{-1,1\} \in V$ be neighboring variables, i. e., they differ on one input. Let $\tilde{x}$ be the input that f and f' differ on. Let us condition on whether $\tilde{x} \in \{x_1, \dots, x_4\}$. As there are eight elements of $\{-1,1\}^3$, both cases occur with half probability.

Case $\tilde{x} \notin \{x_1, \dots, x_4\}$. In this case, $A_i(f) = A_i(f')$ for all i, so $A(f)$ always equals $A(f')$.

Case $\tilde{x} \in \{x_1, \dots, x_4\}$. In this case, one of the two strings $(f(x_1), \dots, f(x_4))$ and $(f'(x_1), \dots, f'(x_4))$ has an even parity and the other string has an odd parity. Without loss of generality, assume that $(f(x_1), \dots, f(x_4))$ has odd parity.

Over the random choice of the b_i, the string $(b_1 f(x_1), \dots, b_4 f(x_4))$ is distributed like a uniformly random string with an even parity. In particular, the probability that all four entries are the same is $1/4$. When this occurs, then $A(f) = A(f')$. This holds because if,ÃŁ for instance, $(b_1 f(x_1), \dots, b_4 f(x_4)) = (1,1,1,1)$, then $(b_1 f'(x_1), \dots, b_4 f'(x_4))$ has three 1's, and so the majority value is 1.

This means that with $3/4$ probability, $(b_1 f(x_1), \dots, b_4 f(x_4))$ has two 1's and two (-1)'s. Fix the b_i, and consider the randomness over the choice of M. In this case, $A(f)$ will be a uniformly random ± 1 bit, because M is uniformly random when there is no clear majority. On the other hand, $(b_1 f'(x_1), \dots, b_4 f'(x_4))$ will have a clear majority, so $A(f')$ a deterministic value. Thus, in this case, $A(f) = A(f')$ with half probability.

Putting it all together. As a result,

$$\Pr[A(f) = A(f')] = \frac{1}{2} + \frac{1}{2} \cdot \left(\frac{1}{4} + \frac{3}{4} \cdot \frac{1}{2}\right),$$

which equals $13/16$. As this holds for any neighboring functions f and f', we get our desired conclusion, which is that $\mathsf{val}(\mathcal{A}_2^1, V_0 \leftrightarrow V_1) = \mathsf{val}(\mathcal{A}_2^1, V_1 \leftrightarrow V_2) = 13/16$. □

Combining $\mathcal{A}_2^0$ and $\mathcal{A}_2^1$: The final distribution $\mathcal{A}_2$ is given by the mixture $\mathcal{A}_2 = (2/3)\mathcal{A}_2^0 + (1/3)\mathcal{A}_2^1$. Because $\mathcal{A}_2^0$ and $\mathcal{A}_2^1$ are both elements of $\mathsf{R}_2(\mathsf{Had}_3)$, it follows that $\mathcal{A}_2 \in \mathsf{R}_2(\mathsf{Had}_3)$. Furthermore, by combining Propositions 4.5 and 4.6, we see that

$$\mathsf{val}(\mathcal{A}_2, V_0 \leftrightarrow V_1) = \frac{7}{8} \quad \text{and} \quad \mathsf{val}(\mathcal{A}_2, V_1 \leftrightarrow V_2) = \frac{43}{56},$$

as promised by the lemma. □

This completes the construction of the distributions $\mathcal{A}_0$, $\mathcal{A}_1$, and $\mathcal{A}_2$, thereby completing the theorem. □

5 A candidate factor-$3/2$ hardness reduction

5.1 The Game Show Conjecture

Herein we present an interesting problem concerning analysis of Boolean functions. We make a conjecture about its solution which, if true, implies NP-hardness (with quasilinear blowup) of factor-$(3/2-\delta)$ approximating 2-Lin(2) for any $\delta > 0$.

Definition 5.1. Let $g : \{-1,1\}^n \to \{-1,1\}$ be a folded function (i. e., $g(-x) = -x$). The *Game Show*, played with *Middle Function* g, works as follows. There are two personages: the *Host* and the *Contestant*. Before the game begins, the Host secretly picks a uniformly random monotone path π from $(1,1,\ldots,1)$ to $(-1,-1,\ldots,-1)$ in the Hamming cube. (Equivalently, π is a uniformly random permutation on $[n]$.) The Host also secretly picks $T \sim \text{Binomial}(n, 1/2)$. We define the *secret half-path* to be the sequence of the first T edges along π: $(x_0,x_1),(x_1,x_2),\ldots,(x_{T-1},x_T)$. Note that x_T is uniformly distributed on $\{-1,1\}^n$.

The Game now begins, with the current *time* being $t = 0$, the current *point* being $x_0 = (1,1,\ldots,1)$, and the current *function* being $\widetilde{g} = g$. (The current function will always be $\pm g$.)

At each time step $t = 0,1,2,\ldots$, the Host asks whether the Contestant would like to *negate* the current function, meaning replace $\widetilde{g}$ with $-\widetilde{g}$. If the Contestant does not negate the current function there is no cost. However, if the Contestant elects to negate the current function, the Contestant must pay a cost of

$$w(t) := \frac{1}{(1-t/n)^2}. \tag{5.1}$$

After the Contestant makes the decision, the Host reveals to the Contestant what the $(t+1)$th point on the secret half-path is, and the new time becomes $t+1$.

As soon as time T is reached, the Game ends. (In particular, in the unlikely case that $T = 0$, the Contestant does not get to make any decisions.) At this instant, if $\widetilde{g}(x_T) \neq 1$, then the Contestant incurs a further cost of $w(T)$. (It is as though the Contestant is now obliged to negate $\widetilde{g}$.) Thus one can think of the Contestant's goal throughout the Game as trying to ensure that $\widetilde{g}(x_T)$ will equal 1, while trying to minimize the total cost incurred by all negations.

We define $\mathrm{cost}(g)$ to be the least expected cost that a Contestant can achieve when the Game Show is played with Middle Function g.

To get a feel for the Game Show, let us make some observations. First, as mentioned, the negation cost $w(t)$ is an increasing function of time; i. e., the later it is in the Game, the more costly it is for the Contestant to negate $\widetilde{g}$. The cost to negate at the beginning of the Game is $w(0) = 1$ and the cost to negate when the Game ends is $w(T) \sim 4$ (with very high probability, since $T = (1/2 \pm o_n(1))n$ with very high probability). As a consequence, we always have $\mathrm{cost}(g) \leq 2 + o_n(1)$. The reason is that the Contestant can always use the strategy of never negating $\widetilde{g}$ unless obliged to at the end of the Game. In this case, the final evaluation will be $g(x)$ where x is uniformly random. By oddness of g, this evaluation is -1 with probability exactly $1/2$, and only in this case does the Contestant suffer a cost, namely $4 \pm o_n(1)$ (with high probability).

It can be shown that the best Middle Function g for the Contestant to play with is any (positive) dictator, $g = d_i$, say. It is easy to check that the Contestant's best strategy is the obvious one: negate if and only if the Host restricted coordinate i to -1 on the previous turn. To estimate the expected cost of this strategy, first note that the probability the Host restricts coordinate i throughout the course of the game is $1/2$. If the Host never restricts coordinate i then the Contestant will have cost 0. Otherwise, conditioned on the Host restricting coordinate i over the course of the game, the Contestant will have cost $w(t^*)$, where t^* is "essentially" uniformly distributed on $\{1, 2, \ldots, n/2\}$. At this point it is natural to introduce the "continuous" time parameter $u = t/n$, which ranges in $[0, 1/2]$ (with very high probability), as well as the function

$$W(u) := w(un) = \frac{1}{(1-u)^2}\,, \tag{5.2}$$

which increases from 1 to 4 on $[0, 1/2]$. The distribution of $u^* = t^*/n$ is "essentially" uniform on $[0, 1/2]$. More precisely, one may check that up to $o_n(1)$ errors, the expected cost to the Contestant conditioned on coordinate i being restricted is just the average value of W, namely

$$\int_0^{\frac{1}{2}} W(u) \cdot 2du = 2\,.$$

Thus we finally conclude that $\mathrm{cost}(d_i) \sim (1/2) \cdot 2 = 1$.

Let us now look at the best strategy when the Middle Function is a *negated* dictator; i. e., let us try to determine $\mathrm{cost}(-d_i)$. Playing the Game Show with Middle Function $-d_i$ is more stressful for the Contestant because at the beginning of the game we have $\widetilde{g}(x) = -1$. Assume the Contestant elects not to negate $\widetilde{g}$ for a while at the beginning of the Game. If ever the Host restricts the ith coordinate to -1 then the Contestant can relax, knowing that no costs at all will be incurred. However as time progresses without the ith coordinate being restricted, the Contestant will naturally get more and more nervous that the game will end with $\widetilde{g}(1, 1, \ldots, 1) = -1$, forcing a cost of essentially 4. On the other hand, if the Contestant decides to "preemptively" negate, there is still some chance that the ith coordinate will subsequently be restricted before the game ends, forcing the Contestant to negate *again*. Actually, it is not hard to show that the best strategy for the Contestant is of the following form, for some value $u_0 \in [0,1/2]$: "If ever the Host restricts the ith coordinate to -1, negate $\widetilde{g}$ if necessary and then never negate again. Otherwise, wait until the continuous time hits u_0 and then negate $\widetilde{g}$." For example, the $u_0 = 0$ case of this strategy involves negating immediately at the game's beginning (incurring cost 1) and then playing the optimal strategy for a positive dictator (incurring expected cost $1 \pm o_n(1)$). The total expected cost is $2 \pm o_n(1)$. As another example, the $u_0 = 1/2$ case of this strategy is the generic strategy of never negating unless forced to at the game's end. This case *also* has an expected cost of $2 \pm o_n(1)$. In fact, one can do a short calculation to show that the expected cost is $2 \pm o_n(1)$ for *every* value of u_0. This is by design: the particular cost function W is *the unique function with this property*.

We have concluded that $\mathrm{cost}(d_i) \sim 1$ and $\mathrm{cost}(-d_i) \sim 2$. To now state our conjecture about the Game Show, we need a piece of notation; for $g : \{-1,1\}^n \to \{-1,1\}$ and "negation pattern" $b \in \{-1,1\}^n$, we write g^{+b} to denote the function defined by $g^{+b}(x) = g(b_1x_1, \dots, b_nx_n)$. Roughly speaking, our conjecture about the Game Show is that for every odd g, the average value of $\mathrm{cost}(g^{+b})$ over all b is at least $3/2$. To be precise, we need to be concerned with averaging over merely pairwise-independent distributions on b.

Game Show Conjecture. Let $g : \{-1,1\}^n \to \{-1,1\}$ be odd and let $\mathcal{D}$ be any distribution on $\{-1,1\}^n$ which is pairwise-independent and symmetric (meaning $\Pr_{\mathcal{D}}[b] = \Pr_{\mathcal{D}}[-b]$). Then

$$\mathop{\mathbf{E}}_{b \sim \mathcal{D}}[\mathrm{cost}(g^{+b})] \geq \frac{3}{2} - o_n(1)\,.$$

Our motivation for making the Game Show Conjecture is the following result.

Theorem 5.2. *Suppose the Game Show Conjecture is true. Then it is* NP*-hard to approximate* 2-Lin(2) *(and hence also* Max-Cut*) to factor* $3/2 - \delta$ *for any* $\delta > 0$.

We remark that given a Middle Function g, in some sense it is "easy" to determine the Contestant's best strategy. It can be done with a dynamic program, since the Game Show is essentially a 2-Lin(2) instance on a tree graph. Nevertheless, we have been unable to prove the Game Show Conjecture. We will discuss some of our efforts in Section 5.3. First, however, we will prove Theorem 5.2.

5.2 Proof of Theorem 5.2

The proof is by construction of a gadget as in Definition 2.26.

Theorem 5.3. *Suppose the Game Show Conjecture is true. Then for each k, there exists a* (c,s)*-gadget reducing Max-*Had_k *to Max-*2-Lin(2) *satisfying*

$$\frac{s}{c} \geq \frac{3}{2} - o_k(1)\,.$$

Via Corollary 2.28, this shows that for every $\varepsilon > 0$, it is NP-hard to approximate 2-Lin(2) to factor $3/2 - o_k(1) - \varepsilon$. Thus, by taking k large enough and ε small enough so that $o_k(1) + \varepsilon \leq \delta$, we get Theorem 5.2.

Now we prove Theorem 5.3.

Proof of Theorem 5.3. Set $n := 2^k$ (previously we have used K for this number, but for this proof we will use n). For the gadget $\mathcal{G}$, let $\{-1,1\}^n$ denote its variable set as usual, and let Z be the set of $2n$ primary variables. For reasons that will be clearer later, we will call the variables of $\mathcal{G}$ the Contestant Strategy variables. As in the definition of a (c,s)-gadget, we need only consider assignments $A : \{-1,1\}^n \to \{-1,1\}$ which are folded.

We will add one twist to this construction: we will have an additional collection of variables, identified with $\{-1,1\}^n$, called the Middle Function variables. We will write $g : \{-1,1\}^n \to \{-1,1\}$ for assignments to these variables, and we will use folding here as well so that each g can assumed to be folded. We remark that it would actually be okay if the Middle Function variables and the Contestant Strategy variables were identified; however, we find it conceptually clearer to separate them, and it does not affect our analysis of gadget's quality.

We now describe the constraints we put on our gadget; these are highly reminiscent of the Game Show described in the previous section. All of the constraints are equality tests along Hamming edges (either within the Contestant Strategy/Middle Function hypercubes, or between them). We will henceforth refer to gadget variables as "points," and assume that n is at least a sufficiently large universal constant.

Overall Gadget Test $\mathcal{G}$:
With probability δ, run the Average Sensitivity Test; with probability $1-\delta$, run the Game Show Test.

Average Sensitivity Test:
Choose a uniformly random edge (y,y') in the Middle Function hypercube and test that $g(y) = g(y')$.

Game Show Test:
Choose a random primary point $x_0 \in Z$ in the Contestant Strategy cube. Choose a random path $(x_0,x_1),(x_1,x_2),\dots,(x_{n-1},x_n)$ from x_0 to $x_n := -x_0$. Choose T to be a Binomial$(n,1/2)$ random variable, conditioned on being in the range $n/2 \pm \sqrt{n\log n}$. Choose $t \in [T]$ such that $\Pr[t = t]$ is proportional to $w(t)$ (as defined in (5.1)). Finally, if $t < T$ then test that $A(x_{t-1}) = A(x_t)$; otherwise, test that $A(x_{t-1}) = g(x_T)$. (In the former case, both points are taken from the Contestant Strategy cube; in the latter case, x_{t-1} is taken from the Contestant Strategy cube and x_T is taken from the Middle Function cube.)
Here δ will be some decreasing function of n which we specify implicitly later. We first prove a little lemma:

Lemma 5.4. *Let $1 \le t \le n/2 + \sqrt{n\log n}$ and write $u = t/n$. Then in the Game Show Test,*

$$\Pr[t = t] = \frac{W(u)}{n} \cdot (1 \pm o_n(1)),$$

where W is defined as in (5.2).

Proof. By definition, all we need to do is show that the "constant of proportionality" in the Game Show Test, namely $\sum_{i=1}^{T} w(t)$, is equal to $n(1 \pm o_n(1))$, uniformly for each outcome of T. Since w is an increasing function, this discrete sum is bounded between the integrals $\int_0^T w$ and $\int_1^{T+1} w$. Using the fact that $\int_0^{1/2} W = 1$, it is easy to compute that both of the bounding integrals are $n \pm O(\sqrt{n\log n})$ when T is $n/2 \pm \sqrt{n\log n}$. $\square$

It is easy to see that in both the Average Sensitivity Test and the Game Show Test, we have complete symmetry with respect to the *direction* in $[n]$ of the edge being tested for equality. Thus, for any dictator function d_i, the probability of rejecting when $A = g = d_i$ is indeed precisely $1/n$. Thus, we need only show that $s \geq (3/2 - o_n(1))/n$ for $\mathcal{G}$ to prove Theorem 5.3.

Theorem 5.5 (Soundness)**.** *Assume the Game Show Conjecture. Suppose A's assignments to the $2n$ primary points Z are chosen uniformly at random. Then regardless of how g and the remaining values of A are chosen, the probability that the Overall Gadget Test rejects is, in expectation, at least*

$$\frac{3/2 - o_n(1)}{n},$$

provided that $\delta = o_n(1)$ is suitably chosen.

Proof. Let us ignore the Average Sensitivity Test for a moment and focus on the Game Show Test. It is evidently somewhat similar to the Game Show as played with Middle Function $g : \{-1,1\}^n \to \{-1,1\}$. In brief, the key differences are: (i) the Game Show Test starts its path from a random point in Z, rather than from $(1,1,\ldots,1)$; (ii) in the Game Show Test, the Contestant/A-chooser's job is even harder than in the Game Show, because the entire strategy A must be fixed before the Game begins. In other words, it is as though the Contestant must act at time t independently of what happened prior to time t.

Having given a little intuition, let us elaborate by carefully phrasing the operation of the Game Show Test in language similar to that of the Game Show. We incorporate into the Game Show Test A's random assignment to the primary points Z; we can imagine that the Host announces uniformly random values $A(z)$ for each $z \in Z$ that the Contestant must use. In the next step of the Game Show Test, we have the Contestant fix an odd Middle Function g; it is important to note that the Contestant gets to do this *after* seeing the random values $(A(z))_{z \in Z}$. Next we can imagine that the Host *secretly* picks a uniformly random primary point $z_0 \in Z$ and a random half-path from it, $(z_0, z_1), \ldots, (z_{T-1}, z_T)$. The Host will be testing equality of A's values on a random (according to w) edge along this half-path, using the value of g instead of A for the last point along the half-path. However in the Game Show *Test*, the Contestant must fix an entire strategy $(A(x))_{x \notin Z}$ before the Host reveals which edge is tested.

We will now make things *easier* on the Contestant—this can only decrease the probability of the test rejecting. Specifically, we will not force the Contestant to immediately announce an entire strategy $(A(x))_{x \notin Z}$. Rather, the Host will reveal the edges (z_0, z_1), (z_1, z_2), ... one-by-one, just as in the Game Show, and will only require the Contestant to decide on $A(z_t)$ in the tth step of this process. Note that $A(z_0)$ is already fixed, as is $g(z_T)$. Once z_T is revealed, the Host will *then* choose t as in the Game Show Test and do the equality-test on the tth edge.

Now let us make a few more viewpoint changes, so that the Game Show Test becomes even more similar to the Game Show. As it has now been described, the Game Show Test starts at a random primary point $z_0 \in Z$, and the Contestant is obliged to use the Host's initially randomly chosen value $A(z_0)$. Let us change this so that once the Host chooses $z_0 \in Z$ at random, the function g is immediately replaced by $\widetilde{g} = A(z_0) g^{+z_0} = g^{+A(z_0)z_0}$. (The last equality uses the fact that g is odd.) In this way, we may equivalently assume that (as in the Game Show) the random half-path always originates from $(1,1,\ldots,1)$, and that the Contestant is obliged to use the assignment $A(1,1,\ldots,1) = 1$. Now as the Game Show Test proceeds, when the Host reveals the tth edge, the Contestant is allowed to specify whether $A(z_t)$ should be *equal* to

$A(z_{t-1})$, or equal to its *negation*. Note that it is "costly" for the Contestant to choose negation, in the sense that it yields an "unequal" edge that will increase the Host's rejection probability by $w(t)$. This process proceeds until z_T is reached, whereupon the Contestant is committed to the final assignment value $g(z_T)$. In our final viewpoint change, instead of allowing the Contestant to either "keep" or "negate" the value assigned at time $t-1$, it is equivalent to allow the Contestant to either keep $\widetilde{g}$ or replace it by $-\widetilde{g}$. The latter choice corresponds to creating an "unequal" edge and incurring cost (rejection probability) $w(t)$. The fact that the Contestant is obliged to use the initial assignment 1 (recall we initially multiply g^{+z_0} by $A(z_0)$) in the test corresponds to the fact that in the Game Show, the Contestant is obliged to end on 1.

It may seem as though we have by now shown that the Game Show Test is equivalent to playing the Game Show with Middle Function $g^{+A(z_0)z_0}$, where $z_0 \in Z$ is chosen uniformly at random—in the sense that the rejection probability of the test is equal to the expected value of $\mathrm{cost}(g^{+A(z_0)z_0})$. However there is one catch: in the Game Show Test, g may be chosen *after* the random assignments $(A(z))_{z\in Z}$ to the primary points. The remainder of the proof is devoted to showing that the Contestant can not effectively "take advantage" of this.

For this we return to the actual Overall Gadget Test, which performs the Average Sensitivity Test with probability δ and the Game Show Test with probability $1-\delta$. (Note that our theorem statement tolerates the loss of factor-$(1-\delta)$ in soundness here.) The purpose of the Average Sensitivity Test is to ensure that the chosen g must essentially be a junta. More precisely, we see that if the chosen g has average sensitivity exceeding $(3/2)/\delta$ then the Average Sensitivity component of the Overall Gadget Test already rejects with probability exceeding $(3/2)/n$. Thus we can assume the chosen g has average sensitivity at most $(3/2)/\delta$. It follows from Friedgut's Junta Theorem [12] that g must be δ-close to a junta on some $J = 2^{O(1/\delta^3)}$ variables. Using the fact that g is odd, one can also ensure that this junta is odd.[1] Next, note that the Game Show Test only involves g with probability

$$\frac{W(1/2)}{n}(1 \pm o_n(1)) \le \frac{5}{n}$$

(using Lemma 5.4). Furthermore, when it *does* involve g, the point on x_T on which it involves g is nearly uniformly random in $\{-1,1\}^n$. The difference from uniform randomness comes because we conditioned T to lie in the range $n/2 \pm \sqrt{n \log n}$; however, T lies outside this range only with probability $o_n(1)$. Thus we see that if we simply replace g with its δ-close odd J-junta, we only affect the Overall Gadget Test's rejection probability by at most $(5/n)(\delta + o_n(1))$, an amount we can absorb in the theorem statement. In summary, we may freely assume that the chosen g is always an odd *junta* on $J = 2^{O(1/\delta^3)}$ coordinates.

Finally, to complete the proof by applying the Game Show Conjecture, it would remain to show that with probability $1-o_n(1)$ over the initial random choice of $(A(z))_{z\in Z}$, for *all* choices of J out of n coordinates, the projection of the distribution $A(z_0)z_0$ to the coordinates J is pairwise independent and symmetric. This is not quite correct, but in Lemma 5.6 below we show that each projection is $O(\delta)$-close in total variation distance to being simultaneously pairwise-independent and symmetric. This is sufficient to complete the proof. □

Lemma 5.6. *Suppose n is sufficiently large as a function of δ. Suppose that for each of the $2n$ strings $z \in Z$ a uniformly random bit a_z is chosen. Then except with probability $o_n(1)$, for every fixed set of $J = J(\delta)$*

[1] The proof shows g is close to $\mathrm{sgn}(\sum_{S\subseteq \mathcal{J}} \widehat{g}(S)\chi_S)$ for some $|\mathcal{J}| \le J$, using an arbitrary convention for sgn(0). One need only ensure that any sgn(0) choices that arise are made in an oddness-preserving way.

coordinates in $[n]$ (in particular, for $J = 2^{O(1/\delta^3)}$), the uniform distribution on the set of strings $(a_z z_J)_{z\in Z}$ is $O(\delta)$-close (in fact, $o_n(1)$-close) to being simultaneously pairwise-independent and symmetric.

Proof. We begin just by showing the pairwise-independence property; here we will not need that J is small compared to n. For any particular pair of coordinates (i,j) in $[n]$ the list of two-bit strings $(z_{\{}(i,j)\})_{z\in Z}$ has $n/4$ equal pairs and $n/4$ unequal pairs (since Walsh–Hadamard columns are orthogonal). Thus when the bits a_z are chosen, in the list $(a_z z_{\{(i,j)\}})_{z\in Z}$ we will see each of the four possible two-bit strings $n/8 \pm O(\sqrt{n\log n})$ times except with probability $\ll 1/n^2$. Thus by taking a union bound over all pairs of coordinates (i,j), it follows that except with probability $o_n(1)$ we have that all projections of $(a_z z)_{z\in Z}$ onto two coordinates are $\widetilde{O}(1/\sqrt{n})$-close to uniform.

Next we consider the symmetry property. Fix any subset $\mathcal{J} \subset [n]$ of J coordinates. Let us consider, for each string $x \in \{-1,1\}^J$, how many times it occurs in the list $(z_J)_{z\in Z}$. Some variables x have at most $\sqrt{n}$ occurrences. However even collectively, these constitute only $2^J\sqrt{n}$ out of the $n/2$ strings, and thus they contribute only $o_n(1)$ total probability mass to the uniform distribution on $(z_J)_{z\in Z}$. As for the remaining strings $x \in \{-1,1\}^J$, each occurs at least $\sqrt{n}$ times. Thus when the bits a_z are chosen, nearly equally many occurrences of $\pm x$ will be formed. Taking into account the need to union-bound over all 2^J strings and indeed all $\binom{n}{J}$ subsets $\mathcal{J}$, we still get that except with probability $o_n(1)$, for all $\mathcal{J}$ of cardinality J, the projection of $(a_z z)_{z\in Z}$ onto the J-coordinates is $O(\sqrt{J\log n}/n^{1/4})$-close to symmetric.

Finally, we claim that if a distribution on J-bit strings is $o_n(1)$-close to symmetric and has all 2-bit marginals $o_n(1)$-close to uniform, then it is has total variation distance at most $2J^2 \cdot o_n(1) = o_n(1)$ from being simultaneously symmetric and pairwise-independent. To see this, we can begin with the $o_n(1)$-nearby symmetric distribution; it still has all its 2-bit marginals at most $2o_n(1)$-close to uniform, and all of its 1-bit marginals are exactly uniform. Now we can apply the "correction procedure" from [2] to deduce that the resulting distribution is $2J^2 o_n(1)$-close to being pairwise-independent. It only remains to observe that this correction procedure maintains symmetry, since it merely mixes the distribution with various symmetric distributions (namely, distributions of the form "uniform on $\{x : x_i x_j = 1\}$" for distinct $i,j \in \mathcal{J}$). ☐

This finishes the (Completeness) and (Soundness) cases of $\mathcal{G}$, giving us Theorem 5.3. ☐

5.3 Regarding the Game Show Conjecture

As mentioned, we are unable to prove the Game Show Conjecture. For the record, we describe here some of our ideas toward proving it. Since we are not claiming any theorems in this section, we will not be completely precise.

As we have already seen, it seems more natural to think of a "continuous" time parameter $u = t/n$ that starts at $u = 0$ and ends at $u = 1/2$. (Thinking of n as large, the ending time will indeed be $u = 1/2 \pm o_n(1)$ with high probability.) In fact, we believe it is even more natural to use a different continuous parameterization of time. Specifically, define the *time remaining* parameter s by $s = \ln(2-2u)$; i. e., $u = 1 - \exp(s)/2$. As time runs from $u = 0$ up to $u = 1/2$, the "time remaining" runs from $s = \ln 2$ down to $s = 0$. The idea behind this rescaling is that now the Host restricts coordinates according to an exponential clock of rate $1/n$. Note from (5.2) that the cost to the Contestant of negating $\widetilde{g}$ with s time remaining is

$$W(s) = 4\exp(-2s)\,. \tag{5.3}$$

Suppose we have some current function $\widetilde{g}$ and the time remaining is s. Let us define $\mathrm{cost}_{\widetilde{g}}(s)$ to be the expectation of the Contestant's remaining cost, assuming an optimal strategy; note that $\mathrm{cost}(\widetilde{g}) = \mathrm{cost}_{\widetilde{g}}(\ln 2)$. For the two constant functions we have:

$$\mathrm{cost}_{+1}(s) = 0\,,$$
$$\mathrm{cost}_{-1}(s) = 4\exp(-2s)\,.$$

The latter equality holds because whenever the current function $\widetilde{g}$ gets restricted to the constant function -1, it is in the Contestant's best interest to immediately negate (because the negation cost is an increasing function of time).

As we alluded to earlier, for general $\widetilde{g}$ there is a "dynamic program" for computing $\mathrm{cost}_{\widetilde{g}}(s)$. (Actually, because s is a continuous parameter, it is more like a "differential equation.") The "base case" for the dynamic program is

$$\mathrm{cost}_{\widetilde{g}}(0) = \begin{cases} 0 & \text{if } \widetilde{g}(1,1,\dots,1) = 1, \\ 4 & \text{if } \widetilde{g}(1,1,\dots,1) = -1. \end{cases} \tag{5.4}$$

In general, we can compute $\mathrm{cost}_{\widetilde{g}}(s+ds)$ given knowledge of $\mathrm{cost}_f(s)$ for all subfunctions f of $\pm\widetilde{g}$. The fact that the Contestant is allowed to actively negate $\widetilde{g}$ causes some complications, so let us begin by considering a *lazy* Contestant, meaning one who uses the (possibly nonoptimal) strategy of never negating $\widetilde{g}$ unless it gets restricted to the constantly -1 function (or unless the game ends and negation is "forced").

Writing $C_{\widetilde{g}}(s)$ for the analogue of $\mathrm{cost}_{\widetilde{g}}(s)$ in the case of a lazy Contestant, we have the same base case (5.4). As for the general formula, suppose that $\widetilde{g}$ depends on r coordinates and that we consider the time remaining dropping from $s+ds$ to s. Let $u = 1-\exp(s)/2$ as usual. It is easy to see that each of $\widetilde{g}$'s relevant coordinates has probability $du/(1-u)$ of being restricted. Since $u = 1-\exp(s)/2$, this precisely equals $-ds$, and hence in going from $s+ds$ to s time remaining, each coordinate has probability ds of being restricted. Thus we deduce the "dynamic programming" formula:

$$C_{\widetilde{g}}(s+ds) = r\cdot ds\cdot \operatorname*{avg}_{\widetilde{g}'}\{C_{\widetilde{g}'}(s)\} + (1-r\cdot ds)\cdot C_{\widetilde{g}}(s)\,,$$

where the average is over all functions $\widetilde{g}'$ gotten by restricting one coordinate of $\widetilde{g}$ to be -1. Let us write

$$A_{\widetilde{g}}(s) = \operatorname*{avg}_{\widetilde{g}'}\{C_{\widetilde{g}'}(s)\}\,,$$

and also approximate $C_{\widetilde{g}}(s+ds) = C_{\widetilde{g}}(s) + \frac{d}{ds}C_{\widetilde{g}}(s)$. Then after rearrangement, the above dynamic programming formula becomes the differential equation

$$-C_{\widetilde{g}}(s) = r(C_{\widetilde{g}}(s) - A_{\widetilde{g}}(s))\,.$$

The solution to this ODE is

$$C_{\widetilde{g}}(s) = r\exp(-rs)\cdot \mathcal{L}_r A_{\widetilde{g}}(s)\,, \tag{5.5}$$

where $\mathcal{L}_r$ denotes the operator defined by

$$\mathcal{L}_r A(s) = \int_0^s \exp(ry) A(y)\, dy + \text{const}\,,$$

with the value of const being determined by the initial condition, $C_{\widetilde{g}}(0) \in \{0,4\}$. With these formulas in hand one can directly compute the following formulas for the two $r = 1$ functions:

$$\begin{aligned} C_{d_i}(s) &= 4\exp(-s) - 4\exp(-2s)\,, \\ C_{-d_i}(s) &= 4\exp(-s)\,. \end{aligned}$$

It was previously argued that the lazy strategy is optimal when the Middle Function is a dictator d_i, and the first formula above confirms that $\text{cost}(d_i) = 4\exp(-\ln 2) - 4\exp(-2\ln 2) = 1$. Furthermore, observe that

$$C_{-d_i}(s) = C_{d_i}(s) + W(s)\,.$$

The left-hand side is the expected cost to the Contestant when using the lazy strategy on a negated dictator; the right-hand side is the expected cost if the Contestant decides to negate $-d_i$ to d_i at time s. Notice that we have equality for all s. This is precisely by design; as mentioned earlier, we chose the negation-cost formula $W(s)$ so that when the Middle Function is a negated dictator, all strategies of the form "negate if and only the relevant restriction has not occurred by time s_0" are equally good, including the lazy strategy.

We have $\text{cost}(d_i) = 1$ and $\text{cost}(-d_i) = 4\exp(-\ln 2) = 2$, hence $\mathbf{E}_{b\sim\mathcal{D}}[\text{cost}(g^{+b})] = 3/2$ whenever $\mathcal{D}$ is symmetric and g is a dictator or negated dictator. To confirm the Game Show Conjecture, what we need to show is that for $\mathcal{D}$ symmetric and pairwise-independent we have

$$\mathop{\mathbf{E}}_{b\sim\mathcal{D}}[\text{cost}(g^{+b})] \geq \frac{3}{2}$$

for all odd g.

Next we consider functions with exactly 2 relevant variables. There are actually no such *odd* functions, but we still need to analyze them since they can arise at intermediate points in the game. From (5.5) one may compute:

$$C_{\text{AND}_2}(s)\,, = 8(\exp(s) - 1 - s)\exp(-2s)\,, \qquad C_{\text{OR}_2}(s)\,, = 8s\exp(-2s)\,, \tag{5.6}$$

$$C_{\text{NOR}_2}(s)\,, = 4\exp(-2s)\,, \qquad C_{=_2}(s)\,, = 4(2\exp(s) - 1 - 2s)\exp(-2s)\,, \tag{5.7}$$

$$C_{\neq_2}(s)\,, = 8(\exp(s) - 1)\exp(-2s)\,, \qquad C_{x\wedge\neg y}(s)\,, = 4(\exp(s) - 1)\exp(-2s)\,, \tag{5.8}$$

$$C_{x\vee\neg y}(s)\,, = 4\exp(s)\exp(-2s)\,, \qquad C_{\text{NAND}_2}(s)\,, = 4(2\exp(s) - 1)\exp(-2s)\,. \tag{5.9}$$

Note that $C_{\text{NAND}_2}(s) > W(s) + C_{\text{AND}_2}(s)$ for all $s > 0$. This implies that the lazy strategy is not optimal for the Contestant when the function is NAND_2. It is not hard to show that the best strategy for the Contestant involves immediately negating NAND_2 to AND_2 whenever it arises. For all other functions above the lazy strategy is optimal, i. e., $\text{cost}_g(s) = C_g(s)$; but for NAND_2 we have

$$\text{cost}_{\text{NAND}_2}(s) = W(s) + \text{cost}_{\text{AND}_2}(s) = 4(2\exp(s) - 1 - 2s)\exp(-2s)\,.$$

Now we can consider 3-bit functions. The only odd ones (up to symmetry) are $\chi_{\{1,2,3\}}$ and Maj_3^{+b} for $b \in \{-1,1\}^3$. It is an exercise to confirm the Game Show Conjecture for all parity functions, so let us focus on the majority-type functions. For them we will introduce the more general notation $\mathrm{LTF}_{a_1,\ldots,a_r}(x) = \mathrm{sgn}(a_1x_1 + \cdots + a_rx_r)$. From (5.5) one may compute:

$$\begin{aligned} C_{\mathrm{LTF}_{1,1,1}}(s) &= 24(1-\exp(-s)+s\exp(s))\exp(-3s)\,, \\ C_{\mathrm{LTF}_{1,1,-1}}(s) &= 8(\exp(2s)-s\exp(s)-1)\exp(-3s)\,, \\ C_{\mathrm{LTF}_{1,-1,-1}}(s) &= 4(2\exp(s)-2s-1)\exp(-2s)\,, \\ C_{\mathrm{LTF}_{-1,-1,-1}}(s) &= 4(3\exp(s)-2)\exp(-3s)\,. \end{aligned}$$

One can show that in fact cost $= C$ for the first three of these functions. However this is not true for the last function, namely $-\mathrm{Maj}_3$. Here we have $C_{-\mathrm{Maj}_3}(s) > C_{\mathrm{Maj}_3}(s) + W(s)$, implying that sometimes the Contestant should negate $-\mathrm{Maj}_3$ to Maj_3. Indeed, now one should consider the overall "dynamic program" more carefully, to incorporate the fact that the Contestant is allowed to negate. Extending the differential equation reasoning above, one finds that it is optimal for the Contestant to negate $\widetilde{g}$ at time s_0 if and only if

$$A_{\widetilde{g}}(s_0) \le A_{-\widetilde{g}}(s_0) + W(s_0) + W'(s_0)/r\,.$$

In particular, when $\widetilde{g} = -\mathrm{Maj}_3$, this condition is equivalent to

$$\mathrm{cost}_{\mathrm{NOR}_2}(s_0) \le \mathrm{cost}_{\mathrm{OR}_2}(s_0) + W(s_0)/3\,.$$

Using the formulas in (5.6), one directly calculates that the least s_0 for which we have equality above is $s_0 = 1/3$. It follows that the optimal strategy for $-\mathrm{Maj}_3$ is to negate if and only if the time remaining reaches $1/3$ without any relevant coordinates being restricted. Taking this into account, we ultimately determine:

$$\mathrm{cost}_{-\mathrm{Maj}_3}(s) = \begin{cases} 24(1-\exp(-s)+s\exp(s))\exp(-3s)+4\exp(-2s) & \text{if } s \le 1/3, \\ 12(2+\exp(s)-2\exp(1/3))\exp(-3s) & \text{if } s \ge 1/3. \end{cases}$$

By substituting $s = \ln 2$, we can state the optimal costs for all reorientations of Maj_3:

$$\begin{aligned} \mathrm{cost}(\mathrm{LTF}_{1,1,1}) &= 6\ln 2 - 3 \approx 1.159\,, \\ \mathrm{cost}(\mathrm{LTF}_{1,1,-1}) &= 3 - 2\ln 2 \approx 1.614\,, \\ \mathrm{cost}(\mathrm{LTF}_{1,-1,-1}) &= 3 - 2\ln 2 \approx 1.614\,, \\ \mathrm{cost}(\mathrm{LTF}_{-1,-1,-1}) &= 6 - 3\exp(1/3) \approx 1.813\,. \end{aligned}$$

The last of these, $\mathrm{cost}(-\mathrm{Maj}_3)$, is surprisingly low. In particular, note that

$$\mathrm{avg}\{\mathrm{cost}(\mathrm{Maj}_3), \mathrm{cost}(-\mathrm{Maj}_3)\} = \frac{3}{2}(1-\exp(1/3)+2\ln 2) \approx .99 \cdot \frac{3}{2}\,. \tag{5.10}$$

This shows that it is *not* sufficient in the Game Show Conjecture merely to assume that the distribution on orientations b is symmetric. However, as the only symmetric pairwise-independent distribution on three bits is the uniform distribution, the case of $g = \mathrm{Maj}_3$ is consistent with the Game Show Conjecture:

$$\frac{1}{8}(6\ln 2 - 3) + \frac{3}{8}(3-2\ln 2) + \frac{3}{8}(3-2\ln 2) + \frac{1}{8}(6-3\exp(1/3)) \approx 1.58 > \frac{3}{2}\,.$$

We do not have a clear strategy for analyzing the general case. A reasonable place to start is to analyze all linear threshold functions, a class of functions closed under restriction, which includes dictators and majorities. In particular, the r-ary "monarchy" function, $\mathrm{LTF}_{r-2,1,1,\dots,1}$ seems like an interesting challenge to analyze.

We make one final remark: As we have seen, the Game Show Conjecture is not correct if the distribution on orientations b need only be symmetric. This is a bit of a shame, because in the proof of the soundness Theorem 5.5, one can ensure symmetry without using any special properties of the predicate being reduced from, besides uselessness. In particular, one could use the older NP-hardness reduction of Samorodnitsky and Trevisan [23] in place of Chan's, which has the advantage [19] of holding with a quasilinear-size blowup. If one hazards the guess that $\mathbf{E}_{b\sim\mathcal{D}}[\mathrm{cost}(g^{+b})] \geq .99\cdot 3/2$ whenever $\mathcal{D}$ is symmetric, a consequence would be that 2-Lin(2) is NP-hard to approximate to factor $.99\cdot 3/2$ with a quasilinear-size reduction; hence, this level of approximation would require nearly full exponential time, $2^{n^{1-o(1)}}$, assuming the Exponential-Time Hypothesis.

6 Limitations of gadget reductions

In this section, we show a limitation to proving inapproximability using gadget reductions from balanced pairwise-independent predicates, that is, predicates ϕ that admit a set $S \subseteq \mathsf{sat}(\phi)$ satisfying Property 2 in Definition 2.4. We show that gadget reductions from ϕ to 2-Lin(2) can not prove inapproximability larger than a factor-2.54 for the deletion version. Note that this applies to the Had_k predicates and to a broader class of predicates that do not necessarily admit a natural group operation.

Theorem 6.1. *Let $\mathcal{G}$ be a (c,s)-generic gadget reducing Max-ϕ to Max-*2-Lin(2)*, where ϕ admits a balanced pairwise-independent set. Then*

$$\frac{s}{c} \leq \frac{1}{1-\mathrm{e}^{-1/2}} \approx 2.54\,.$$

Proof. As before, K is the number of satisfying assignments of ϕ. Recall that the vertex set of $\mathcal{G}$ is $V = \{-1,1\}^K$. Further, via Propositions 2.19 and 2.21, we need only consider folded assignments to these variables, and we can assume $\mathcal{G}$ only uses $(=)$-constraints. Finally, via Proposition 2.29, we can assume that every $(=)$-constraint used by $\mathcal{G}$ is between two variables x and y which are Hamming distance one from each other. Let P be the set of generic primary variables, let $-P$ be their negations, and let $P^{\pm} = P \cup (-P)$ denote the union of the two. Since ϕ is balanced pairwise-independent, we have a set $S \subseteq [K]$ so that for i picked uniformly at random from S, $\Pr_i[u_i = v_i] = 1/2$ for distinct primary variables $u, v \in P$.

Define the similarity between x and y to be the fraction of positions on which they agree $\mathsf{sim}(x,y) := \Pr_i[x_i = y_i]$ and set $\mathsf{sim}(x,P^{\pm}) := \max_{y\in P^{\pm}} \mathsf{sim}(x,y)$. Pairwise-independence allows us to claim that any variable x is strongly similar (i. e., has similarity $> 3/4$) with at most one variable $y \in P^{\pm}$; define y to be x's *closest* primary variable.

Fact 6.2. *For any $x \in V$, if $\mathsf{sim}(x,y) > 3/4$ for some $y \in P^{\pm}$, then $\mathsf{sim}(x,y') < 3/4$ for all other $y' \in P^{\pm}$.*

Proof. If x has $\mathsf{sim}(x,y_1) > 3/4$ and $\mathsf{sim}(x,y_2) \geq 3/4$ for $y_1, y_2 \in P^{\pm}$, then

$$\mathsf{sim}(y_1,y_2) \geq \mathsf{sim}(y_1,x) + \mathsf{sim}(x,y_2) - 1 > \frac{1}{2},$$

contradicting the assumption on ϕ. $\square$

This fact allows us to design the following "threshold-rounding" procedure to construct a distribution $\mathcal{A} \in \mathsf{R}^{\text{gen}}(\phi)$. Let $\mathcal{D}$ be a distribution over $[3/4,1]$ with probability density function $\mathcal{D}(t) = C \cdot \mathrm{e}^{2t}$, for $t \in [3/4,1]$ (and C set appropriately).

1. Pick a random assignment to the primary variables.
2. Pick a number $t \sim \mathcal{D}$. For any variable $x \in V$, call x type 1 if $\mathsf{sim}(x,P^{\pm}) > t$ and type 2 otherwise.
3. Assign all type-1 variables the value of their closest primary variable.
4. Pick a uniformly random dictator d_i and set all the type-2 variables to agree with this dictator.
5. Output the resulting assignment.

Note that the assignments are folded and are random on the primary variables. We analyse the performance of this assignment. Let (x,y) be an edge in $\{-1,1\}^K$ of Hamming weight one. If both $\mathsf{sim}(x,P^{\pm}), \mathsf{sim}(y,P^{\pm}) \leq 3/4$, then regardless of the value of t, x and y will both always be type-2 variables, in which case $\mathcal{A}$ violates the edge between them with the probability of a random dictator, which is

$$\frac{1}{K} \leq \frac{1}{1-\mathrm{e}^{-1/2}} \cdot \frac{1}{K}.$$

On the other hand, suppose without loss of generality that

$$\mathsf{sim}(x,P^{\pm}) > \mathsf{sim}(y,P^{\pm}) \quad \text{and that} \quad \mathsf{sim}(x,P^{\pm}) > 3/4.$$

If we set $s := \mathsf{sim}(y,P^{\pm})$, then $\mathsf{sim}(x,P^{\pm}) = s + 1/K$. Because y is distance one from x, $s \geq 3/4$. Not only that, if y has a closest primary variable, then that variable is the same as x's closest primary variable (this is by Fact 6.2). Now, to calculate the probability that $\mathcal{A}$ violates (x,y), there are three cases:

1. If $t \in [3/4,s)$, then x and y are assigned the value of the same variable in $P^{\pm}$, so (x,y) is never violated in this case.
2. If $t \in [s,s+1/K)$, then y's value is chosen according to a uniformly random dictator assignment, meaning that it is a uniformly random ± 1-bit, independent from x's value. In this case, (x,y) is violated with probability $1/2$.
3. If $t \in [s+1/K,1]$, then both x and y are assigned values according to a random dictator, in which case (x,y) is violated with probability $1/K$.

In total,

$$\begin{aligned}
\Pr[\mathcal{A} \text{ violates } (x,y)] &= \frac{1}{2} \cdot \Pr_{t\sim\mathcal{D}}[t \in [s, s+1/K)] + \frac{1}{K} \cdot \Pr_{t\sim\mathcal{D}}[t \in [s+1/K, 1)] \\
&= \frac{1}{2}\int_{s}^{s+\frac{1}{K}} C\mathrm{e}^{2t}\,\mathrm{d}t + \frac{1}{K}\int_{s+\frac{1}{K}}^{1} C\mathrm{e}^{2t}\,\mathrm{d}t \\
&\le \frac{1}{2} \cdot \frac{C\mathrm{e}^{2s+2/K}}{K} + \frac{1}{K}\int_{s+\frac{1}{K}}^{1} C\mathrm{e}^{2t}\,\mathrm{d}t \\
&= \frac{C\mathrm{e}^{2}}{2K} = \frac{1}{1-\mathrm{e}^{-1/2}} \cdot \frac{1}{K},
\end{aligned}$$

as promised. Here the inequality follows from the fact that e^{2t} is an increasing function. As $\mathcal{G}$ only uses length-one edges, $c = 1/K$. We have just shown that

$$\mathsf{uval}(\mathcal{A};\mathcal{G}) \le \frac{1}{1-\mathrm{e}^{-1/2}} \cdot \frac{1}{K}.$$

Because $\mathcal{A} \in \mathsf{R}^{\text{gen}}(\phi)$, we conclude that

$$\frac{s}{c} \le \frac{1}{1-\mathrm{e}^{-1/2}}. \qquad \square$$

7 Conclusion

As mentioned, we view our factor-$11/8$ NP-hardness result more as a proof of concept, illustrating that the longstanding barrier of factor-$5/4$ NP-hardness for Max-Cut/2-Lin(2)/Unique-Games can be broken. There are quite a few avenues for further work:

- An obvious problem is to derive a better NP-hardness result for 2-Lin(2) by reduction from Had_4 rather than Had_3. As one can always embed our Had_3-based gadget into a standard Had_4-based gadget, this method will always yield a hardness of at least $11/8$. But presumably the optimal Had_4-based gadget will do slightly better.

  Since our analysis of the optimal Had_3 gadget is already somewhat complicated, it might be challenging to analyze the Had_4 case explicitly. A weaker but more plausible goal would be to prove (perhaps indirectly) that there *exists* a $\delta_0 > 0$ such that the optimal Had_4 gadget achieves factor-$(11/8+\delta_0)$ NP-hardness. This would at least definitely establish that $11/8$ is not the "correct answer" either.

- Of course, proving the Game Show Conjecture would yield the improved NP-hardness factor of $3/2$. It may also be simpler to try to prove a non-optimal version of the conjecture, yielding *some* hardness factor better than $11/8$ but worse than $3/2$. Certain ideas we had for trying to prove the conjecture (e. g., distinguishing whether g is "close to" or "far from" being a dictator) might yield such a result.

- Along these lines, it could also be a good idea to prove some form of the Game Show Conjecture that only relies on the distribution $\mathcal{D}$ on orientations b being symmetric, rather than pairwise-independent. As mentioned, this would allow one to reduce from the Samorodnitsky–Trevisan hardness result, yielding nearly full-exponential hardness under the ETH. Since our proof of Theorem 5.2 reduces from Chan's hardness result, it has the unfortunate aspect that we only get factor-$(3/2-\delta)$ hardness (under ETH) for algorithms running in time $2^{n^{\delta'}}$ for some $\delta' = \delta'(\delta)$ that we did not bother to make explicit.

- For Max-Cut, our work establishes NP-hardness of $(\varepsilon, C\varepsilon)$-approximation for any $C < 11/8$, but only for $\varepsilon \le \varepsilon_0$ where ε_0 is some not-very-large constant arising out of Proposition 2.35. It would be nice to get a direct Max-Cut gadget yielding a larger ε_0, like the $\varepsilon_0 = 1/8$ we have for 2-Lin(2).

- A recent result of Gupta, Talwar, and Witmer [14] showed NP-hardness of approximating the (closely related) Non-Uniform Sparsest Cut problem to factor-17/16, by designing a gadget reduction from the old $(4/21, 5/21)$-approximation hardness of Håstad [15]. A natural question is whether one can use ideas from this paper to make a direct reduction from Had_2 or Had_3 to Non-Uniform Sparsest Cut, improving the NP-hardness factor of 17/16.

- We are now in the situation (similar to the situation prior to [21]) wherein the best NP-hardness factor we know how to achieve for 2-Lin(q) (or Unique-Games) is achieved by taking $q = 2$. In fact, we do not know how to achieve an NP-hardness factor better than 5/4 for 2-Lin(q) for any $q > 2$, even though 2-Lin(q) is presumably *harder* for larger q. Can this situation be remedied?

- In light of the limitations described in Section 6, it makes sense to seek alternative methodology of establishing improved NP-hardness for 2-CSPs. An example showing that this is not at all hopeless comes from the decade-old work of Chlebík and Chlebíková [9], which shows NP-hardness of approximating 2-Sat(-Deletion) to factor $8\sqrt{5} - 15 \approx 2.8885$. Their result is essentially a small tweak to the Vertex-Cover hardness of Dinur and Safra [10] and thus indeed uses a fairly radical methodology for establishing two-bit CSP-hardness, namely direct reduction from a specialized Label-Cover-type problem.

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